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# HAWK MACH-III
# Intelligent Maintenance Tutor
# Design Development Report

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This Research Note presents the design and development of the HAWK MACH-III demonstrator. The MACH-III system will be an intelligent tutoring system centering on instruction in the diagnosis and correction of faults at the level of organizational maintenance in the AN/MPQ-57 High-Powered Illuminator Radar (RAM/HIPIR) component of the HAWK air defense system. Formative and summative evaluation of the system and courseware will be conducted within the program of instruction for HAWK Firing Section Mechanics (MOS 24C) conducted at the U.S. Army Air Defense Artillery School (USAADASCH), Fort Bliss, Texas.

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HAWK MACH III INTELLIGENT MAINTENANCE
TUTOR DESIGN DEVELOPMENT REPORT

## EXECUTIVE SUMMARY


Requirement:

To improve individual troubleshooting skills of Army personnel by developing an intelligent tutor demonstrator for effective maintenance training of the HAWK missile system.

Procedure:

The MACH-III will be a stand-alone tabletop training device, suitable for use in individual or classroom settings. Since the MACH-III will offer the 24C trainee virtually unlimited access to HIPIR simulations in normal and faulted modes without the need to use actual radar equipment, it can be applied in the USAADASCH 24C POI to increase the quantity and quality of "near-hands-on" experience available to the 24C trainee.

MACH-III will be able to demonstrate correct troubleshooting technique to the trainee, provide guided practice in troubleshooting, and analyze and critique trainee performance on specific problems. To accomplish this, MACH-III will incorporate a hierarchical simulation of the RAM/HIPIR which is able to generate explanations of function and fault genesis. An articulate troubleshooting expert will support the interface to the trainee during troubleshooting exercises. This expert will be capable of reproducing procedures which track Government issued fault isolation procedures (FIPs) for the HIPIR as well and of generating principled approaches to fault isolation when the range of the FIP is exceeded. Capabilities for control of problem presentation to the trainee and for authoring new material complete the system design.

Findings:

The approach to instruction will emphasize the development within the 24C trainee of an accurate mental model of the organization, function, and operation of the HIPIR and its

various components, through guided practice in simulated troubleshooting activities. The MACH-III will function as a "two-dimensional" training device, providing diagrammatic representations of HIPIR controls, indicators, components, interconnections, and organization. As such, the primary focus of MACH-III training will be on the cognitive processes which support effective troubleshooting, and not as much on the physical actions associated with actual equipment repair.

Utilization of Findings:

This paper presents the design of the HAWK MACH-III demonstrator for maintenance training. Application of this system model may allow Army trainers the ability to improve instruction in troubleshooting and maintenance skills for military personnel.

**ACKNOWLEDGMENTS**

Many individuals in BBN and in the Government have assisted us in the preparation of this document. We wish especially to acknowledge the contributions of Allan Collins and Ed Smith to the development of our concepts of the troubleshooting task and effective troubleshooting training methods. In addition, Bruce Roberts assisted in the development of approaches to implementation of our training concepts.

Within the Government we have received significant assistance from the U.S. Army Air Defense Artillery School, Ft. Bliss, Texas. Col. Robert S. Hardy, Jr., DOTD, USAADASCH, assisted us in obtaining access to training and maintenance specialists within the school. Sheldon Smith of DOTD helped us understand the relation of MACH-III to other USAADASCH initiatives in training technology, while Rex Jenkins of DOTD coordinated our contacts with other USAADASCH groups, especially the HAWK Department, Firing Section Branch, from which we drew most of our expert advisors. Joe Manna and Sgt. Carl Fox spent many days helping us understand the HIPIR radar and appropriate troubleshooting techniques. A number of HIPIR maintenance personnel cheerfully endured hours of questioning and testing on our behalf. They include Sgt. Anthony Archuleta, Sgt. Ralph Livingston, SP4 Rodger Chartier, and SP4 Andre Henry.

Finally, we acknowledge the patient support and advice which we received from Dr. Joseph Psotka and Dr. Wayne Gray of the U.S. Army Research Institute for the Behavioral and Social Sciences, which made this research possible.

# 1. INTRODUCTION

This document presents our approach to the design and development of the HAWK MACH-III demonstrator. It is organized as an introduction, followed by five chapters presenting the theoretical framework, the target capabilities, the application to the target population, and the development and implementation plans.

This introduction provides important information requisite to an understanding of the direction and scope of our implementation plans. The first section below describes the immediate background to the development effort in terms of the project origins, the equipment application, and the training problem. It concludes with a statement of the objectives of our work, as they have emerged from initial examination of the background.

The second section summarizes our development approach for this research, highlighting decisions reached, plans made, and areas which will be the subject of further study.

## 1.1 Project Background

The research, design, and development activities of the HAWK MACH-III demonstration project are being performed by BBN Laboratories Inc., a wholly owned subsidiary of Bolt Beranek and Newman Inc., under contract to the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI). Significant assistance in this project is being provided by the U.S. Army Air Defense Artillery School (USAADASCH), Ft. Bliss, Texas.

The MACH-III system is intended to be a training device in which state-of-the-art techniques in artificial intelligence and cognitive science are applied to support the training of novices in troubleshooting complex electronic devices at the organizational maintenance level.

For the purposes of the present development and demonstration project, the AN/MPQ-57 High-Powered Illuminating Radar (HIPIR) component of the HAWK air defense missile system has been selected as the complex electronic device for which organizational maintenance training will be performed by MACH-III. The USAADASCH training program for HAWK Firing Section Mechanics (MOS 24C) has been selected as the Program of Instruction (POI) within which the usefulness of the MACH-III system will be demonstrated and assessed.

### 1.1.1 The HAWK HIPIR

The AN/MPQ-57 HIPIR is a mobile, continuous-wave (CW) frequency-modulated (FM) steerable dish antenna radar system which serves as the target engagement component of the HAWK air defense system. The HIPIR is able to accept remotely specified target designation information, perform a target acquisition scan, establish tracking lock on the target, compute and provide optimum launch data to the HAWK missile launcher (LCHR), illuminate the tracked target while the missile (MSL) flies to the point of interception, and verify target destruction.

Although the original design of the HIPIR is more than thirty years old, several major Product Improvement Program (PIP) cycles have upgraded parts of the basic design to incorporate modern fabrication techniques (e.g., the use of solid-state integrated circuit technology), to reduce system cost, to improve maintainability, and to improve system performance in modern ECM environments.

As a result of these many retrofits and in-production modifications, the overall electronic design of the current generation HIPIR displays an almost archaeological layering of technologies of varying vintages and complexities. The earliest parts of the radar are fairly simple in design, but use technologies which are unrelated to modern design practice. The most recently upgraded parts of the radar make full use of complex and/or high-speed digital logic, presenting a formidable challenge to detailed functional comprehension.

As information within the radar flows from the ancient to the modern domain, and back, it must repeatedly pass through interfacing subsystems, where shaft position is translated to or from analog voltage, or analog voltage is converted to or from digital data. Since the HAWK system, including the HIPIR, will remain in service beyond the year 2000, and since additional PIP cycles are already being developed, it is likely that the heterogeneity of the system will not decrease.

As a result of these considerations, the total body of general background knowledge of electronics required for thorough understanding of the HIPIR (at all maintenance levels) encompasses elements of radar system design practice spanning more than thirty years.

The HIPIR is functionally organized into ten subsystems. Five of these subsystems have a major function in overall radar operation--the transmitter (XMTR), the receiver (RCVR), the digital signal processor (DSP), the antenna positioning (servo) system (APS), and the target intercept computer (TIC). Of these major subsystems, the TIC is by far the most primitive, being a mechanical analog device supported by various synchro interfaces to the remainder of the HIPIR.

Organizational maintenance of the remaining four major subsystems is supported by automatic built-in test equipment (BITE). The HIPIR BITE subsystem is able to isolate critical sections of circuits, inject standardized test signals, measure outputs at test points, and report exceptions to the operator. Automatic BITE consists of a preprogrammed sequence of tests which are performed on the HIPIR system, the servo, the transmitter, or the receiver/signal processor, when the operator presses one of four TEST buttons. Within a few minutes, the BITE subsystem indicates if the subsystem tests GOOD or reports the location of the fault.

While the BITE system is able to solve a great many problems of organizational maintenance, its coverage is incomplete, based on certain assumptions which cannot be automatically verified, and subject to various failures.

Four subsystems of the HIPIR are not subject to BITE (besides the TIC). These are the heating/cooling subsystem, the communications subsystem, the power distribution subsystem, and the tracking adjunct subsystem (TAS). The communications subsystem is quite simple, and does not interface to any other part of the HIPIR. The heating/cooling system is somewhat more complex, contains liquid circuits which are inconvenient to maintain, and can have indirect effects on the operation of other subsystems, particularly the transmitter. The TAS is a recently fitted optical/video antenna aiming device, which is essentially independent of the rest of the HIPIR system.

The BITE does not directly test the power distribution subsystem; it is assumed that any failure in power distribution will affect one of the directly tested functions. As a result, basic maintenance doctrine for the HIPIR requires that, whenever a BITE fault is reported, the power distribution system must be checked before any attempt is made to correct the fault. More primitive, non-automatic test devices are built into the radar to support troubleshooting the power distribution system and the TIC.

Not all BITE indications of module failure are accurate. Many interfaces exist between modules within a subsystem, providing paths for the propagation of failures, and resulting in erroneous indications of fault location.

The automatic BITE is, except for the signal processor, the most complex subsystem of the HIPIR. Although it is largely built from modern digital logic, and therefore relatively reliable, it controls mechanical and/or electronic switches located throughout most of the HIPIR. The BITE does not really test itself, and has only the most primitive imaginable human interface, so that diagnosis of BITE failures is very difficult and correction is usually accomplished by exchange of suspect modules.

Established organizational maintenance procedures for the HIPIR make extensive use of the BITE. Traditional troubleshooting techniques, such as signal tracing and checking cables for continuity and shorts, are employed in the absence of BITE, or when BITE has pinpointed a specific trouble area. When BITE diagnosis and fault correction, together with various documented remedial procedures, fail to make the HIPIR operational, the expert 24C must be able to turn to detailed functional schematic diagrams to continue the troubleshooting process.

### 1.1.2 The USAADASCH POI

The USAADASCH POI for MOS 24C occupies a total training interval of 39 weeks. Twenty weeks, or approximately one-half of this period, is devoted to training specific to the HAWK air defense system. Major elements of the HAWK system covered include the HIPIR, the LCHR, and the loader. Eight weeks are devoted to detailed study of the HIPIR.

The content of the HIPIR portion of the 24C POI is organized to cover overall HIPIR system operation as well as each of the ten HIPIR subsystems--the transmitter (XMTR), the receiver (RCVR), the digital signal processor (DSP), the servo, the TIC, the tracking adjunct system (TAS), the power distribution system, the heating/cooling system, the system test circuits, and the communications (COMMO) system. While this listing defines the structure of the POI, it fails to disclose the pedagogic approach to presentation of the material.

Instruction of 24C trainees at USAADASCH in HIPIR organizational maintenance is supported by four classes of non-administrative personnel--technical writers, conference instructors, platform instructors, and equipment maintenance staff. It is not uncommon for individuals to work in several of these groups during a tour of duty at USAADASCH; however, the platform instructors and equipment maintenance staff are military personnel, and the majority of the conference instructors are civilian employees of the Army.

The technical writers are responsible for creation and maintenance of the lesson plans and associated materials supporting the 24C POI.

The conference instructors conduct lectures about radar, circuit, and maintenance theory for groups of sixteen or twenty-four 24C trainees.

The platform instructors work with the actual HIPIR equipment to demonstrate correct troubleshooting procedures and to assist students in hands-on troubleshooting. Groups of eight 24C trainees work on a single HIPIR.

The equipment maintenance staff are responsible for repair of the radars used by the platform instructors. They constantly test the equipment to assure that it contains no faults other than ones which the platform instructors deliberately introduce for training purposes. At times they are called in to discover and correct a fault inserted by training purposes which was improperly documented or unsuccessfully removed.

The instruction presented in conference is essentially a walk-through of the entire HIPIR documentation set. This walk-through not only includes basic nomenclature, HIPIR organization, HIPIR operation, and routine maintenance checks, but also extends to a full presentation of all standard troubleshooting procedures and a detailed discussion of the operation of all circuits of the HIPIR.

Since the theory presented in many of these lectures is very detailed and presumes a good grasp of detailed radar system function, much of it is not well understood by the majority of the 24C trainees. Since the 24C is not authorized or qualified to repair the HIPIR at the component level dealt with in the most detailed part of these lectures, job performance may not be seriously affected by this lack of comprehension. The absence of any need to understand the HIPIR at the level of detail presented in many of the lectures may also be demotivating to some 24C trainees.

The instruction presented in the platform exercises affords the 24C trainee an opportunity to attempt fault diagnosis and correction on an actual HIPIR. Within each instructional unit, a number of possible system faults have been identified which can be easily created in the HIPIR. The platform instructor induces one of these faults into a radar and then guides the 24C trainee through its detection, isolation, and correction.

Since the faults are necessarily limited to defects which will not seriously damage the radar, and which can be easily induced and removed, the 24C training experience is somewhat unrealistic. Since groups of eight trainees work on the radar at one time, the individual opportunity to "learn by doing" is very limited.

After reviewing the 24C POI, after extensive discussions with all classes of USAADASCH instructional personnel, and after examining the 24C training materials and the RAM/HIPIR technical manuals, we conclude that the training experience has four important components which contribute significantly to the future job performance of the 24C.

1. *Nomenclature.* The POI familiarizes the 24C with the nomenclature, terminology, and physical layout of the HIPIR. He learns to identify the major functional parts of the radar in terms of their correct names, and positions within the HIPIR. He learns the decomposition of the functional parts into replaceable components.

2. *Documentation.* The 24C learns the organization of the various TM's which support HIPIR operation and maintenance. He learns the representation of the functional parts and

replaceable components of the HIPIR in the documentation. He becomes familiar with the applicability of the various elements of the documentation to different phases of the operation, maintenance, and troubleshooting process. He is instructed in the use of the documentation to identify a faulted component or connection or to determine the need for adjustment of a subsystem.

3. *Procedures.* The 24C learns how to operate the HIPIR for the purpose of performing routine checks and adjustments. He learns to power up the radar through various standby states, and power it down. He learns to observe indications of proper radar operation, and to take appropriate corrective action. He learns to perform system and subsystem tests using the automatic BITE and related equipment (e.g. the TIC approach/recede switch and the high voltage power supply test set (HVPSTS)) and to replace failed components as indicated.

4. *Conceptual framework.* The 24C acquires a general and partial familiarity with the HIPIR taxonomy, layout, and functionality which supplies the cognitive framework (or mental model) which he will use to organize, relate, interpret, and understand his future experience. The completeness, consistency, and accuracy of this mental model, together with the 24C's ability to expand and correct it as needed, will strongly affect his ability to learn from experience on-the-job and to progress to expert status as a radar mechanic.

### 1.1.3 MACH-III Objectives

The MACH-III prototype is intended to demonstrate the application of the techniques of instructional and cognitive science and artificial intelligence to the development of an intelligent tutoring system. The development of an effective and useful prototype will require research into the cognitive basis of applicable troubleshooting skills and into novel methods of knowledge representation by computer.

In addition to providing a direction for supporting research, the MACH-III prototype development effort should produce a training device of demonstrable value to the 24C POI. This value will ultimately be reflected in improved job performance by new 24C graduates. We believe this objective can best be achieved by designing the MACH-III to provide augmented hands-on experience in troubleshooting in a setting which will emphasize development of the fourth area of POI content described in section 1.1.2 above, the development of a sound conceptual framework to use in classifying and interpreting future experience.

The objective of the MACH-III trainer will therefore be to enhance and to expedite the acquisition by the 24C trainee of an accurate mental model of the function and operation of the HIPIR in the context of typical troubleshooting tasks. This model should accurately depict the actions and relationships of the components of the HIPIR at varying levels of aggregation, and the effects of faulty components on HIPIR and subsystem performance. The model should be elaborated in sufficient detail to related directly to the system components on which the 24C exercises organizational maintenance, the field-replaceable modules of the HIPIR.

Initial research in cognitive issues supporting this development activity will focus on analysis and understanding of mental models of HIPIR operation and malfunction employed by 24C's with varying degrees of experience. As partial MACH-III implementations become available for experimental work, cognitive research focus will shift to examination and critique of the effects of interaction with MACH-III on trainee mental models. Such research results will guide and shape MACH-III development and fine tuning.

Research in artificial intelligence supporting the development activity will focus on development of a strategy for effective and efficient hierarchical simulation of the HIPIR in normal and faulted modes of operation. This effort cannot be divorced from the logical analysis of HIPIR organization and operation by subject matter experts or from the study of effective mental models held by experienced troubleshooters.

## 1.2 Design Overview

The MACH-III system will be an intelligent tutoring system centering on instruction in the diagnosis and correction of faults in the RAM/HIPIR of the HAWK air defense system. The approach to instruction will emphasize the development within the 24C trainee of an accurate mental model of the organization, function, and operation of the HIPIR and its various components, through guided practice in simulated troubleshooting activities.

The MACH-III will be a stand-alone tabletop training device, suitable for use in individual or classroom settings. Since the MACH-III will offer the 24C trainee virtually unlimited access to HIPIR simulations in normal and faulted modes without the need to use actual radar equipment, it can be applied in the USAADASCH 24C POI to increase the quantity and quality of "near-hands-on" experience available to the 24C trainee.

The MACH-III will function as a "two-dimensional" training device, providing diagrammatic representations of HIPIR controls, indicators, components, interconnections, and organization. As such, the primary focus of MACH-III training will be on the cognitive processes which support effective troubleshooting, and not as much on the physical actions associated with actual equipment repair. For example, a student will be able to give instructions to the trainer like "Disconnect cable P1 from high voltage unit A3" or "Remove card A4 from the signal processor" without having to perform the physical task described or to describe its method of performance in detail.

### 1.2.1 Cognitive Issues

A significant body of recent research in cognitive science indicates that an expert's knowledge of complex systems differs significantly from that of a novice. Specifically, experts have relatively accurate and complete mental models of system operation, function, and interconnection, which support their knowledge and application of troubleshooting procedures. In addition, experts display an understanding of the functioning of a system at different levels of aggregation, ranging from the broad functional level to the level of specificity actually required on the job.

The results of preliminary experiments we have conducted at USAADASCH indicate that 24C trainees do not acquire substantially effective mental models during their brief period of training on the HIPIR, but some 24C's with increasing periods of experience on-the-job eventually succeed in acquiring such models. In a series of interviews about how the HIPIR works, we have found that novice 24C's focus on physical aspects of the the radar and emphasize the distribution of power through the system. Experts, on the other hand, talk about functional aspects of the radar and emphasize the flow of information. The expert's model facilitates the job of interpreting symptoms and narrowing down possible fault locations. The limited conceptual understanding of the radar demonstrated by students appears to arise from the limited time available for hands-on work diagnosing faulty HIPIR operation during the platform exercises, and the focus of these exercises on the physical organization and assembly of the radar.

The MACH-III will attempt to remediate this deficiency by affording 24C trainees the opportunity to practice troubleshooting skills on a HIPIR simulation which is organized to emphasize the functional structure of the radar system. When the MACH-III trainer is integrated in to the 24C POI, it will become the principal vehicle for practical development of cognitive skills required for troubleshooting. The program of platform exercises can then be more aptly focused on transference of these skills to the physical equipment and training in equipment assembly and disassembly.

### 1.2.2 Instructional Design

The MACH-III is conceived as a supplementary training device which supports, but does not fully attempt to substitute for, other parts of the 24C POI. 24C trainees will receive a brief orientation to the MACH-III early in their course of instruction and will perform exercises on the MACH-III in conjunction with each instructional segment of the POI.

The MACH-III will support the POI by providing an inspectable symbolic simulation of HIPIR operation at three different levels of component aggregation. The simulation will be able to reproduce patterns of faulty HIPIR operation associated with specific faults defined at the level of field-replaceable components, and smoothly reflect the effects of these faults on major functions and subsystems of the radar.

Inspection of the simulation will be controlled by an articulate expert. It will demonstrate, guide the student through, and monitor the student's progress in the various activities which support effective troubleshooting, such as observation, correlation, diagnosis, and corrective action. Troubleshooting expertise embodied in this system will be based on practical maintenance doctrine derived from consultations with experienced 24C's, standard procedures documented in HIPIR TM's, and formal inferencing procedures generally applicable to systems.

Many important issues relating to the instructional design of the MACH-III lie in the area of the man-machine interface. The experience of the trainee will necessarily be very different with the MACH-III than in the platform exercises. It is important that the MACH-III human interface not require the trainee to master unusual skills which will impede transference of the training to operational equipment. In addition, the patterning and pacing of presentations, while limited to a two-dimensional image, should be attractive enough to sustain trainee interest.

In general, the MACH-III visual presentations will be diagrammatic and symbolic. Since the 24C will ultimately have to work with existing HIPIR TM's, no systems of designation or description should be used which conflict with this material. On the other hand, it is desirable to extend the presentation style of the TM's to achieve worthwhile instructional goals, as long as care is taken to avoid creating a permanent reliance on these extensions.

As the detailed design of MACH-III instructional material develops, we plan to evaluate the usefulness of animation, color, and speech to enhance the student interaction.

### 1.2.3 Delivery Hardware

The basic delivery device used in MACH-III development is a Symbolics 3645 workstation, which supports an operating environment based on the CommonLisp language. This equipment, or its equivalent, will be commercially available in a desktop package during calendar year 1986. Lower-cost, higher-density packagings of compatible systems will probably become commercially available during calendar year 1987, and would be used for expanded testing of the developed MACH-III at USAADASCH, if available.

Depending on the results of various trials of the developing system, the basic workstation could easily be expanded by addition of a speech synthesizer (at minimal additional cost) or a color graphics system (at substantial additional cost). We expect that the addition of a speech synthesizer may eventually prove worthwhile, and think that, color graphics will prove to have great instructional benefits.

The delivery hardware configuration does not, as presently envisioned, include a random-access videodisk subsystem or a graphics overlay generator for videodisk images. It is likely that the addition of such equipment to the MACH-III would enable the system to take on more of the 24C instructional tasks related to nomenclature, physical structure of the HIPIR, and transference of cognitive skills. However, the development of an image library for such purposes and its integration with other parts of the MACH-III design is a major mechanical effort which would, we feel, detract from the more important goal of improving the development of 24C cognitive skills. We also feel that a program of platform exercises will always be required to support these other training goals.

### 1.2.4 Delivery Software

MACH-III delivery software will be programmed in CommonLisp or ZetaLisp for execution in the standard environment of a Symbolics Lisp workstation. The software will be designed, insofar as possible, as a generic intelligent tutoring system (ITS) without specific reference to the HIPIR subject area. The main components of such a system are the system simulation and problem-solving expertise, the student model, and the tutorial strategies.

In the MACH-III the implementation of these very abstract and general ITS components will reflect our understanding of the HIPIR subject matter, cognitive issues related to troubleshooting practice, and instructional issues relating to the existing 24C POI. The very great complexity of the HIPIR itself and its associated organizational maintenance doctrine dictates strong emphasis on the area of problem-solving expertise in MACH-III development.

While the mere representation and use of compiled expert knowledge in an ITS may not itself be pedagogically useful, no ITS which lacks such information can be technically relevant.

In MACH-III we will use a hierarchical simulation of the HIPIR which incorporates, at one time, a mechanical model of the functions of the system, the expert mental model of the system which the student is to acquire, and an analytical framework for interpreting student performance.

The HIPIR will be simulated at three distinct levels. At the *subsystem* level the entire radar operation will be described in terms of the interrelationships of the major subsystems (e.g., XMTR, RCVR, APS). At the *functional* level, each subsystem will be described in terms of the interrelationships of the functions which support its operation. At the *replaceable module* level, each subsystem or function will be described in terms of the physical connections between the specific field-replaceable devices from which it is built.

The operation of each subsystem, function, and module comprising the HIPIR simulation can be altered to reflect the presence of characteristic faults. Knowledge of the presence of these faults is propagated along signal paths through the model. Faulty signals may induce faulty operation by other components of the model.

The simulation will provide mechanisms by which the trainee can obtain symbolic characterizations of signals, component characteristics, component operation, and system actions with the fidelity required to support organizational maintenance.

Procedural troubleshooting knowledge (as opposed to structural knowledge of the HIPIR) will be embodied in an articulate expert troubleshooter. This program will be capable of executing practical HIPIR maintenance procedures, assembling observations of system operation, analyzing these observations in accordance with established TM directives, performing corrective actions on the simulation, and developing limited inferential chains to explain its actions and to interpret the propagation of faulty operation through the simulation.

The troubleshooter will operate in three basic modes. In the *demonstration* mode it will apply its knowledge to troubleshoot the simulation and provide explanations of the basis for its actions. In the *guided practice* mode it will allow the student to control the activities of the troubleshooting process. The troubleshooter will monitor student progress, request reasons for various student actions, and offer suggestions for action on request. In the *monitor* mode the troubleshooter will observe and score student performance.

These three basic modes can be modified by the action of various mixed-initiative capabilities. These permit the student to interrupt demonstrations to assume control of the troubleshooting process and to yield control during guided practice to observe the expert solution to an exercise. In addition, the troubleshooter will be capable of "replaying" student actions recorded in the monitor mode, providing relevant critique.

In addition to the simulator and the troubleshooting expert, a separate curriculum control program will be provided which is able to present narrative explanations, to administer conventional CAI segments, and to establish the operational modes of the simulator and the troubleshooter during troubleshooting exercises.

Tools will also be provided to assist in the creation of system models and curricular materials by modification of MACH-III data structures. The degree of development achieved in these tools and in the curriculum control program will be affected by the level of difficulty experienced in achieving our objectives for the simulator and the troubleshooter.

## 2. THEORETICAL FRAMEWORK

This chapter provides an overview of techniques and results from the areas of cognitive science and artificial intelligence which we will apply to the design and development of an intelligent tutoring system demonstration for the HAWK HIPIR. As such, it identifies background and explanatory material to support the technical discussions occurring in later chapters.

### 2.1 Cognitive Science

Our approach to the design of an intelligent maintenance trainer stems from recent work in cognitive science on how people acquire domain specific knowledge. Much of this research has focused on what people know about physical systems. Studies have been conducted on the expert's knowledge of complex physical systems, such as steam plants and automotive systems, as well as on the novice's misconceptions of common physical phenomena, such as the trajectory of a ball or the flow of current in a circuit. Much of this research is summarized in a book, *Mental Models*, written at BBN by Dedre Gentner and Al Stevens (1983).

The term mental model refers to an understanding of a system that includes knowledge of the possible states of each component as well as the temporal and causal links between components. Mental models are abstract in the sense that some aspects of the system are invariably lumped together or ignored. Mental models are concrete in the sense of being imaginable and "runnable." A mental model can serve as a tool for problem solving by allowing the thinker to mentally "run" the model to observe the effects that a change in one part of the system has on other parts. Such processes are necessary for making inferences and predictions about the functioning of the system in different circumstances. This research, therefore, has important implications for training people to operate and maintain equipment.

Two notions emerge from this body of research that have particular relevance for the design of an intelligent maintenance trainer. The first is that in order to teach troubleshooting, it is necessary to impart some understanding of how the system works. The claim is that it is not sufficient to teach a set of procedures. Rather, the student must acquire an understanding, or mental model, of the function and interconnection of the relevant components.

The second important idea to emerge from the literature is that the functioning of a system can be understood at different levels. The process of evaporation, for example, can be understood in terms of rain and clouds, in terms of molecules leaving and returning to a body of water or, at a deeper level, in terms of the electrical attraction between molecules. In other words, models of a system can be constructed at different levels of specificity. The claim is that the best way to teach the expert's model is to teach a series of models that will bring the student to increasingly deeper levels of understanding. Three subclaims follow from this line of research: First, the initial model taught the student should contain a small number of relatively familiar entities. Secondly, there should be enough different levels so that the mapping between levels is not too difficult. Finally, the last model should reflect the level of specificity that will actually be required on the job.

Evidence will now be presented in support of each of these claims.

### 2.1.1 The Importance of System Understanding for Troubleshooting

The claim that the learning of maintenance procedures needs to be grounded in an understanding of the system to be maintained comes from several sources. The most direct evidence comes from an extensive study of avionics technicians undertaken by the LRDC group at the University of Pittsburgh (Gitomer, 1984; Glaser *et al.*, 1985). The researchers first selected individuals who were rated as most and least effective at problem solving by their job supervisors. Supervisor ratings were validated by administering problems similar to those encountered on the job. A series of experimental tasks was then administered to all subjects to determine what knowledge and skills contributed to the group differences. One of the significant findings to emerge from this research was that the skilled group knew more about the overall functioning of the system, as well as about specific troubleshooting procedures. These differences emerged in spite of the fact that the two groups had received identical training. The two groups did not differ in knowledge that was not directly related to the job, (e.g., about electrical components that never had to be considered in detail). These results suggest that the successful troubleshooters had acquired an understanding of the system, or mental model, that was optimal for their particular task.

An appropriate model would be expected to enhance problem solving in a troubleshooting context for a couple of reasons. First, a model can serve to reduce the memory load. Technicians who have acquired a mental model do not have to remember dozens of fixed procedures, nor do they have to expend effort in searching through a manual. Many specific procedures can be generated from a suitably complex mental model, thus a mental model is cognitively economical. Secondly, a model provides flexibility. A technician who has an appropriate mental model can deal with unfamiliar situations not covered by fixed procedures.

A second line of evidence for the power of a model as an instructional tool comes from research on instructions. Kieras and Bovair (1984) have shown that providing students with information about the structure and functioning of a technical system prior to their receiving instruction in how to use that system produces faster and more error-free learning. Students who were not given the opportunity to acquire a mental model of the system failed to reach the same level of proficiency as those who did learn the model, even though the system was a relatively simple one. The ability to localize faults in the system was similarly enhanced by providing a model. Using a similar procedure, Smith and Spoehr (1985) showed that having a model facilitated memory of the components, comprehension of instructional steps, accurate execution of the steps, and reasoning about a new procedure. In a similar vein, Smith and Goodman (1984) have shown that when readers are given information about the overall structure and function of a simple electrical circuit, they are better able to read and comprehend procedural instructions on how to construct the circuit.

Thus, the psychological literature provides much support for the position that mental models are potentially powerful tools for reasoning about complex engineered systems. Because such models are memorable, adaptable, and economical and effectively capture the way experts think about physical systems, they provide a basis for more effective troubleshooting.

### 2.1.2 Implications of Levels of Understanding for Teaching

One outgrowth of the work on mental models has been the observation that people's understanding of a physical system often seems to progress through a series of increasingly more specific models. A mental model, in this view, represents a particular level of understanding. Miyake (in press) recorded dialogues between subjects who were attempting to understand how a sewing machine produces a stitch. An analysis of the dialogues showed that subjects understood the functioning of the system at different levels. At the simplest levels they understood that a stitch was created and that two threads interact. More specific was the understanding that the bottom thread goes through the loop of the upper thread and that the bobbin is involved. The precise functioning of the bobbin constituted the deepest level of understanding. In progressing through these levels subjects oscillated between feeling that they understood the device and feeling that there was more to be explained.

Collins (1985) interviewed high school subjects concerning their notions about evaporation and observed that more advanced students described and reasoned about the processes in terms of molecules, while less advanced students spoke about global variables such as clouds and steam. Among those who spoke of molecules, some described aggregate behavior (e.g., escape rate), while others went a step further and analyzed the process in terms of the electrical forces between molecules.

These observations suggest that certain levels of understanding are more intuitive or obvious than others and therefore need to be acquired before other levels can be mastered. The levels approach finds support from recent work on the hierarchical nature of categories (Rosch *et al.*, 1976). This work has shown that basic level terms (like apple) are acquired earlier by children than the *superordinate* (*fruit*) or subordinate (Macintosh) terms and are easier to recall, even for adults.

Work currently in progress at BBN promises to shed more light on the notion of levels of understanding. One such project involves a system to simulate and teach troubleshooting of automobile electrical systems. QUEST was designed so that students acquire increasingly sophisticated models of circuit behavior as they interact with the system. White and Frederiksen (1985) have formulated, and are in the process of refining, a series of such models, each of which is upwardly compatible with subsequently presented, more complex models.

Another ongoing project at BBN concerns the nature of cognitive change. This work is an outgrowth of Collins' work (1985) on high school students' mental models of evaporation and other physical processes. The research raises several important issues pertinent to teaching. Preliminary results suggests that making the student explicitly aware of different levels of explanation may help to prevent misconceptions that arise when a line of reasoning that is appropriate at one level is applied to a different level for which it is not appropriate. Giving a student practice in describing the same phenomenon from the perspective of several different levels may help to eliminate this source of confusion.

A second issue concerns the optimal order in which to introduce models and components, or how the tutoring should be structured. A breadth-first approach would entail teaching all aspects of the system superficially and then taking them up in progressively greater depth on subsequent "passes" through the material. A depth-first approach would entail tracing one component at a time through successive levels.

In short, there seems to be sufficient evidence to justify a levels approach to the training of radar maintenance. There is little research to date, however, to guide this process.

## 2.2 Artificial Intelligence

Troubleshooting systems developed within AI have mostly been of a very shallow kind. They encode the associational or empirical knowledge that allows an expert to go directly from symptoms to fault hypotheses. In fact, this shallowness was the main idea behind so-called expert systems: do not try to reason from first principles, but make use of the many inferential leaps that experts have found to be useful in many years of practice. Lately however, there has been increasing attention to an important drawback of this approach: the apparent uniformity of the associational rules (and the relatively simple control regimes needed to apply them) has led to a neglect of the more complex knowledge representations and control regimes that are needed to make systems more robust and/or capable of explaining their reasoning to users or students. In particular this later capability is fundamental to our effort.

We need a troubleshooting system that can explain why at some point during troubleshooting it is looking for certain symptoms. The answer to this question should both contain the rationale behind the particular empirical symptoms-to-fault rule it is considering and the reason for considering that rule at this point during troubleshooting. The first part will have to refer to the way the particular device works. The second part requires reference to the troubleshooting strategy that is being followed.

A large body of work on reasoning about devices is beginning to address these issues[1]. The fundamental question in this research is how the behavior of a (faulted) device is related to and arises from its structure. The non-mechanistic framework of classical physics, in which system behavior is described by the values of its variables at each time instant, is rejected because it does not provide insight in how a system works. The concepts used by people to explain the workings of a system (cause, feedback, oscillation) remain implicit in this quantitative framework, making it very hard to ground explanations in commonsense physics as encountered in our daily lives. To make this link and capture physical intuition, this research aims at formalizing what is called qualitative reasoning; qualitative because it is not based on numerical (quantitative) equations, but on constraints between qualitative changes in the state of the components ("if the voltage over a resistor increases, the current will also increase", "if the temperature in a closed vessel is increased, its pressure will rise"). The "intuitiveness" of qualitative reasoning is not its only appeal. As Forbus (1984) points out, one of the major advantages of qualitative reasoning for this type of inference is that it works with little and even incomplete information.

Several systems have been built that can generate qualitative accounts of the behavior of a system on the basis of device models (general descriptions of the components and their behavior) and their connectivity. Note that a qualitative account is not the same as a causal

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[1] See, for instance, Vol. 24 of *Artificial Intelligence*, December 1984, and the *SIGART Newsletter* No. 93, July 1985

account. It explains behavior (i.e. input-output relations) as a logical implication of (qualitative) constraints between state variables. A causal explanation on the other hand should be in terms of how the device functions, i.e. how a change in component A causes a subsequent effect on a neighboring component B and so on. De Kleer and Brown (1984) point out that there are two different behaviors: intrastate and interstate, each requiring a causal accounts. Within a state each of a composite device's components remains in the same state and all its variables keep changing in the same way. Between states one or more components change state and the state variables may change in different directions. Interstate behavior can be modeled in a state diagram, but intrastate behavior requires the introduction of some order to the way a new equilibrium is calculated. To this end they introduce the notion of mythical time and a set of heuristics for propagating the calculation in a way that captures mythical causality.

The capability to generate a causal account is fundamental to explanation and prediction, both of correct and faulty devices. Other uses are simulation and diagnosis. Simulation places stricter demands on the way the causal account is constructed. It would be attractive if the reasoning process itself could simulate the behavior of the device. This would require the reasoning to take place as if it were in the device itself, instead of being handled by some external reasoner. The components would, in that view, become special-purpose information processors with only local access to their direct neighbors, instantiating the local constraints specifying the component behavior.

To use such a simulation as an animation "engine", capabilities for handling numeric values will have to be included. Such a direct coupling of simulation and animation with the causal reasoning is different from the approach followed in Steamer, where a separate numerical simulation was used to drive the animation. In the later approach it is very difficult to keep a close coupling between the qualitative reasoning and the quantitative simulation, especially when introducing faults.

The following two subsections discuss techniques of Artificial Intelligence programming applicable to two critical phases of MACH-III operation–the representation of knowledge about troubleshooting procedures, and the efficient simulation of complex systems.

### 2.2.1 Troubleshooting Knowledge Representation

In troubleshooting or diagnosis, the problem is to infer structural changes from erroneous behavior. Sometimes symptoms will be specific enough to point directly to particular faults. These are the cases handled by most of the current troubleshooting expert systems. Few systems know how to handle the more complicated case where the initial symptoms allow a whole set of (very general) fault hypotheses and the system has to engage in differential diagnosis. An example of a medical diagnosis system capable of such a diagnosis is CASNET. This system uses causal relations between symptoms and hypotheses to find the most discriminating tests. However, these causal links are part of its knowledge, and not derived from anatomy and physiology.

Unless the system disposes of complete, precompiled knowledge of the tests for each of the possible hypotheses - in which case the discriminating test might be derived by comparing those tests - the system will have to engage in backward reasoning to find the structural changes that could have accounted for the observed faulty behavior. By predicting other faulty behavior given these changes (by qualitative reasoning), discriminating tests can be derived. This is the approach followed by Davis (1984) and Genesereth (1984). The work of Davis and associates is particularly interesting in that it tries to combine heuristics and general approaches to troubleshooting in a principled way. An algorithmic solution to finding faulty components (in their case an iteration of simulation, dependency-directed backtracking and consistency checking via constraint suspension) is dependent on a number of underlying assumptions: localized failure, single failure, consistent failure, correct schematics and so on. Davis (1984) and Genesereth (1984) see these assumptions as defining one of many possible pathways of interaction (causality) and suggest an ordering of these assumptions that allows the troubleshooter to systematically and in an empirically defensible way relax these assumptions.

It is unlikely that this or similar approaches can be used, as they are, in the MACH-III system. One difficulty arises from the much greater complexity and diversity of the HIPIR. In digital devices the "stuff" flowing between components can always be treated as numbers at all levels of analysis. In the HIPIR, the "stuff" can be power, current, information (such as Azimuth error), or frequency spectrum information. A system such as SOPHIE, which follows a more pragmatic approach, is probably a better example of what will be achievable within this project.

SOPHIE (Brown, Burton & deKleer, 1982) combines local propagation of numerical values (actually ranges) with qualitative rules that infer possible modes of behavior for the various components on the basis of their "device models". This general knowledge is augmented with circuit-specific knowledge that captures the causal relations needed for troubleshooting. This knowledge is represented in the form of behavior trees that relate the modes of behavior of components to that of modules (aggregates of components or "lower" modules) and in the form of state-to-state rules that relate behavior modes of modules to neighboring modules. The latter relation is causal in the interactive sense, the former relation is more one of implication (e.g. "if this module is faulty, this will be because of its components is behaving in a faulty way").

### 2.2.2 Complex System Simulation

A simulation model of the HIPIR will be central to the MACH-III tutoring systems. This simulation is intended to serve two purposes. First, it provides a picture of the radar and its operation as they appear to the 24C radar mechanic. Second, it presents this information in a way which reflects the cognitive perspective on radar organization and operation which we wish the 24C trainee to acquire.

The desired cognitive perspective dictates that the simulation be presented from three distinct, but interrelated viewpoints. To some degree these different viewpoints will correspond to varying levels of aggregation of HIPIR components or different degrees of resolution of the radar into its constituent parts. The three levels we have identified are the ***subsystem, functional,*** and ***replaceable module*** levels.

At the ***subsystem*** level, the HIPIR is to be simulated in terms of such components as the XMTR, the RCVR, the signal processor, the APS, and the TIC, along with appropriate communication pathways between them. This is a very general level that is useful for making general statements about the workings of the HIPIR and the flow of information between the components. There is very low fidelity in relating problems in the system to the manifestations a 24C would observe; however, at this level it is possible to demonstrate the various radar controls and indicators (e.g. lights, dials, meters) and the overall process of HIPIR operation, including system BITE.

The second level is the *functional*. Each *subsystem* can be simulated in terms of its own *functional* components. A *functional* simulation is generally a more detailed picture of a *subsystem* simulation. It provides a basis for a higher fidelity simulation of a fault, relates to a few of the automatic BITE indications, and is the level to which an expert 24C may resort when faced with a particularly vexing problem. A *functional* simulation does not relate well to most the kinds of probes a 24C would perform and it does not address the actual parts a 24C might replace; however, at this level it is possible to demonstrate the way in which various classes of malfunctions affect overall operability and performance of the HIPIR.

The third level and most important level is the level of *replaceable modules*. At this level each module that can be replaced or adjusted by the 24C is simulated. A *replaceable module* model has a close congruence with both trouble shooting doctrine and BITE indications, and can be directly related to extant documentation. The major problem with simulation at the *replaceable module* level is the size and complexity of a complete HIPIR description. Simulating the HIPIR at this level presents a degree of detail that can obscure the overall picture of radar operation and overwhelm the student. The development of a complete cognitive model, for either a prototypical expert or a particular student, would be incomplete. Finally, the computational resources necessary for an honest simulation would reduce interaction with the HAWK MACH-III to little more than a batch operation.

There is good and adequate reason for wanting a model of the HIPIR at each level. An important skill of an expert troubleshooter is the ability to think of the radar and its parts at the appropriate level of detail while addressing a particular problem. A multiple level understanding of the HIPIR is a powerful device for focusing on the components of a problem while abstracting away the unimportant details.

We plan to build a virtual simulation of all levels. This will be a simulation that appears to comprise concurrent simulations at each of the three levels. This will be accomplished by doing the actual simulation for each part at the minimum level necessary for a particular problem with components at higher or lower levels inferring necessary information from meta-knowledge on demand. The advantages of this approach are manifold:

1. A complete picture of the HIPIR can be presented to the student while finessing the problem of a complete simulation,
2. The focusing strategies of the expert can be highlighted,
3. Mental models can be developed and analyzed at any or all of the levels,
4. Lesson presentation, coaching, and student debriefing can be related to the appropriate level,
5. Student misconceptions can be identified at each level and appropriate instructional goals generated, and

6. The simulation model can be developed in an incremental manner as required to support particular lesson objectives.

# 3. TARGET CAPABILITIES

This chapter presents an overview of our best estimate of the goals which can reasonably be attained within the current state-of-the-art in intelligent tutoring systems development, as applied to MACH-III. Subjects discussed include MACH-III modes of operation, tasks and skills, instructional strategy, relationship to POI, instructoı authoring, and record management facilities.

## 3.1 Tasks and Skills

### 3.1.1 Areas of Need

From the cognitive analysis of avionic technicians (Gitomer, 1984; Glaser *et al.*, 1985) and also from our preliminary protocol studies of 24C's, a generalization may be stated: less skilled personnel organize their system knowledge primarily by the locations of physical components, rather than by functions as do the more skilled personnel. This is not surprising considering that 24C students receive instruction primarily at the component and subcomponent (e.g., logic gates) level. Because of the enormous number of components involved, considerable time is spent learning to identify the components. Furthermore, the danger of high voltage severely limits the amount of practical hands-on experience with the radar and the amount of exposure to typical radar problems. The opportunity to practice and thus understand the purpose of the test procedures is consequently limited as well.

Moreover, the documentation is limited in its functional approach, and the student is hard pressed to knit together a coherent view of function tied to physical components. Procedural tests are difficult for the student to implement because of the high voltage danger, the overwhelming number of components involved, and the seemingly repetitive steps to follow. The high level understanding is masked by the detail of procedural implementation and by the difficulty in extracting the relevant information from the documentation, if it is there.

The documentation lacks simple, high-level presentation in terms of flowchart diagrams, an explanation of the purpose and types of steps to be implemented, what components are relevant and what type of information to expect. It has been described as a "branch and get lost" approach by some of the HAWK personnel. The physical dimensions of the documentation make it difficult to use and it is full of errors or omissions. A significant amount of class time is spent having students labelling components, the page on which the wire next appears, what reading or signal to expect, and so forth. Thus, the accessibility to key functional information is lacking.

In our interviews with the 24C instructors, we have heard several comments indicating that the HAWK school's goal is to acquaint the student with the nomenclature, the equipment, and how to use the various pieces of documentation, rather than to actively train the student in radar operation.[2] Operational training is left to the TAC site in places such as Germany or Korea. Aside from the overwhelming amount of detail to absorb, students have a forty-day leave between the end of the HAWK school program and the beginning of the TAC site training. This is a substantial interim period where students can forget the rapidly learned and underutilized material.

Sufficient correct practice (between 1000 and 10,000 trials) is critical for effective troubleshooting (Lesgold, 1985).

The HAWK instructional personnel seemed to concur on this point. During our first visit we asked them what was really critical for good troubleshooting. Their general comments can be summarized as "learning with someone who really knows the radar" (at the TAC site) and "years of experience". These comments can be translated into not only does the student have to know the essential nomenclature, physical layout of the radar, and the documented test procedures and other routines, but he needs a mentor to provide the correct model and the opportunity to practice troubleshooting with guidance. The 24C instructor's comments seemed to indicate that being assigned to a good mentor was a random possibility and that, without this stroke of luck, learning good troubleshooting skills would be difficult.

From the studies on avionics technicians (Gitomer, 1984; Glaser *et al.*, 1985; and Lesgold, 1985) the less skilled airmen were compared to the more skilled airmen in their ability to troubleshoot. The qualitative differences found lacking in the less skilled airmen are described below:

1. They were unable to form a sufficiently detailed initial hypothesis, constrain the "search space"[3] for the problem, test the hypothesis, and form an alternative hypothesis when faced with data which conflicted with the originial hypothesis.

2. They did not understand the function of the entire system, its major subsystems and the components which comprise those subsystems, nor the interrelationships between the subsystems and the interrelationships between the subsystem components.

3. They did not understand the function of the test procedures, i.e., their purpose, what results to expect, and what important subsystems and components were involved.

4. They did not perform the test procedures correctly.

From our preliminary interviews, these same generalizations may be applied to the 24C students. Indeed, many of these findings and observations were substantiated by an interview

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[2]Previous studies on Air Defense systems have shown that fielded units have received deficient levels of training; USAADASCH currently teaches less than fifty percent of the MOS skills, using real equipment, prior to OJT.

[3]a logical reasoning method used to narrow down and eventually isolate the general area of the problem

with a recent graduate (less than one year) of the 24C program, a self-described "average" student. He said that he did understood very little of what he had learned in school[4] and could not fathom why he was required to learn certain information. It was not until he was actually faced with troubleshooting problems on his current job that the purpose of the curriculum content became apparent. In fact, he expressed the wish that he could go back to school, knowing what he knew now.

The shortcomings of his training were evident when we asked him to give a functional description of how the radar worked. Unlike those who had "years of experience", his explanation primarily consisted of what and where the physical components were. Essentially, he could only describe those components on which he had had troubleshooting experience - he often commented that he "didn't know what this bunch of meters and lights do" because he "hadn't worked on it yet".

When asked how he learned about the radar on the job, it was usually in the context of a problem that he had not seen on the job. He usually turned to the resident experts and received a description of the problem, an explanation of how the involved components actually worked, which tests were needed, which part to replace, and how to replace it. This highly motivated 24C explained that it was really important to have someone who could answer his questions, "however stupid" they were.

Thus, the 24C student has great difficulty organizing his knowledge in a meaningful and useful manner, because he lacks:

- a cognitive framework in which to store incoming knowledge for easy retrieval
- concrete, realistic problems as a context in which to learn and to highlight the need for learning certain material or procedures
- a functionally based, easy-to-grasp, organized presentation (lecture, documentation) of the course material
- sufficient guided, hands-on practice in troubleshooting problems
- a mentor who can demonstrate methodology and provide the relevant mental framework, information and guidance as needed

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[4]He added that the instructors were not at fault, because they had too much to teach in too little time.

### 3.1.2 Tasks and Skills to Teach

To lay the groundwork for effective troubleshooting at the TAC site, the 24C MOS need certain prerequisite skills. The following paragraphs describe these background skills:

1. The content area generally covers the specific components, the documentation, and the relevant procedures. These are covered in the HAWK school in a linear manner, rather than in a cognitively organized hierarchy, making comprehension and recall of the system components and procedures difficult. The course needs to provide a cognitive framework where increasingly more specific, complex material can be inserted. By providing the student with a functional framework first, increasingly more specific information can be "plugged in". This framework would start with a functional overview of the entire system. Further study would continue "downward" through the functions of each major subsystem and the functional components of which they are comprised until, finally, the level of individual physical components is met.

2. The student needs to learn the material in a realistic context, i.e., within the context of actual problems, ranging from the simple to the more complex. The students also need exposure to the various classes of typical problems, what gives rise to these problems (weather-related influences, voltage fluctuation, external device problems, etc.), and an explanation of their solutions.[5]

3. The students need sufficient practice in identifying and selecting predetermined solutions for these types of problems. As this skill becomes more automatic, students must actually perform their own procedural solutions on increasingly more complex problems.

4. A functional understanding of the fault isolation procedures must be taught: the student has to understand the purpose of each test, what the tests measure, know which types of tests are applicable under certain circumstances, and particularly, what results to expect from the tests and how to interpret that information.

5. The student must learn to perform the test procedures accurately and efficiently use any equipment, whether built-in or external, employed in those test procedures.

6. The student must learn certain cyclic "meta-skills" critical to problem solving:

    o How to construct a hypothesis about what the problem may be

[5]Experienced troubleshooters often described the lack of preparation for weather-related problems: "In Iran, dust gets into everything. You can't keep it ou....In Germany, it gets cold, and rapidly...always raining... water gets into the waveguide...What happened to that nice radar that was in the building? This one is 6000 miles away on top of a mountain and it's raining like hell. It's hard to cope...the cause is not always the same...they'll do it at different times and...different ways...it's not a doctrinal procedure...it's a thought process that is learned but is not described."

- o How to decide which test procedures will collect the relevant data to confirm or revise the hypothesis

- o How to systematically monitor which actions have been taken and need to be made while trying to isolate the problem

- o How to interpret the information obtained from the test procedures; based on this interpretation of the data, decide how the original hypothesis is effected and what future actions need to be taken

7. Other types of skills often passed along during the mentoring process in an informal manner, are "tricks of the trade". Experts generally have heuristic strategies which often make accomplishing a task easier. There has been mention of these methods during our interviews; if these can be more formally described as part of the expert's troubleshooting knowledge, they need to be incorporated into the instructional program.

These tasks and skills described above fall into four content areas of instruction: domain knowledge, heuristic strategies, self-regulatory strategies, and learning strategies (Collins and Brown, 1986). Domain knowledge includes the knowledge and procedures explicitly identified with a particular subject matter, and is the general focus of schools.

Schools do not generally teach the three strategy areas in a formal way: heuristic strategies help accomplish a task, while self-regulatory (monitoring) strategies help control the process of carrying out the task. These monitoring strategies consist of two components, diagnostic and remedial; students must be explicitly taught to differentiate and apply these skills. Learning strategies help one learn about a new domain, and includes strategies such as requesting help from an expert or simple rehearsal.

These strategies contain those skills which often differentiate good learners from poor ones and thus, should be addressed by any instructional program. The MACH-III simulation and the HAWK instruction must develop, make visually explicit, direct and support these strategy skills, in conjunction with the functionally organized domain-specific knowledge, until the student has internalized them well enough to direct the performing of the test procedures. To the extent that is possible, these areas will be addressed by the HAWK POI and the MACH-III.

## 3.2 Instructional Approach

An essential premise behind the MACH-III system is "learning by doing", i.e., students learn to effectively troubleshoot by doing that very activity. For this activity to occur, the student must simultaneously understand, recall, coordinate and perform the skills and strategies described in the previous section. Each skill and strategy must be explicitly taught and integrated with one another until the student can perform them in context without cognitive overload.

Novice-expert studies (Gitomer, 1984; Glaser *et al.*, 1985) on avionics troubleshooting and physics problem solving (Chi, Glaser and Rees, 1981) indicate that novices seldom generate or infer alternative hypotheses or procedures towards solving the problem. Chi et al hypothesized that the reason novices had difficulty was primarily attributable to a different knowledge organization: experts' knowledge, organized by physics principles, contained not only factual and procedural knowledge, but the conditions for applying those procedures; novices' knowledge, organized by superficial features such as physical objects, contained only factual knowledge.

Our preliminary results show characteristics like those of the avionics technicians: radar experts seem to organize their knowledge by functional operation and, depending on the conditions or symptoms, select relevant procedures for problem resolution; novices organize by physical location and rotely perform procedures without knowing their purpose. In the HAWK program, hypothesis formulation, together with factual and procedural information, will occur in the context of problem solving. Students will be asked to predict possible faults and justify their reasoning throu;·. a series of menus designed to provide relevant choices (e.g., no power, no control signal, broker gear, etc.) Furthermore, students will be provided with problems pertaining to a certain function which require knowing under what conditions to apply certain procedures. In this way, the instruction w.ll be functionally organized into "chunks" containing facts, procedures and the conditions for applying those procedures.

### 3.2.1 Instructional Methods

To effectively teach the 24C MOS troubleshooting skills and strategies, the instructional methodologies must be carefully selected and coordinated. From the research in cognitive and instructional sciences, effective instruction has been shown to contain certain elements (Collins, 1984):

Modelling — An expert demonstrates the task and provides a high-level explanation of what is occuring and why it is done that way. This provides the student with a standard or ideal model against which he may compare his performance repeatedly as needed. A simulated demonstration can provide the student with a tireless, consistent model.

Coaching — The expert observes the student's attempt at performing the task, diagnoses any difficulties, and corrects any errors. During this guided practice, the expert also assures the student when they perform the task correctly. The student essentially begins to differentiate correc' actions from incorrect ones.

This method characterizes the mentor-apprenticeship or the "over the shoulder" learning situation. It is highly productive learning environment, but it has also been a bottleneck in the instructional process, since it is time consuming and requires a low teacher:student ratio. The MACH-III simulation can speed up this interaction with its immediate feedback capabilities.

Inquiry — With this teaching method, the expert systematically questions the student to force them to generate theories about what differentiates correct from incorrect performance for the domain content and strategies involved. With the articulate expert, the MACH-III system can consistently question students to stimulate and support internalization of the strategies necessary for hypothesis generation and problem solving.

Articulation — Having students articulate their domain knowledge or processing through various methods such as inquiry, reciprocal teaching, or group problem solving, is a way to force students to make their thought processes more explicit to themselves and to others. Through these types of interactions, students refine their thinking processes and gradually internalize the roles needed for problem solving, namely the hypothesis generator, the moderator, and the evaluator. By providing students with a menu of possible directive actions, the MACH-III can support, direct, and monitor student performance throughout the problem solving process.

Reflection — Replaying the student's performance and comparing this to the expert's performance provides the student with feedback on their performance and better differentiation of what is considered an ideal model. Through visually explicit displays (possibly flowcharts of actions taken), the student can view an ideal model and compare this with his own performance. (If certain actions must be sequential, while others can be performed in any order, this can be visually differentiated.) This replay capability provides students with a means of monitoring how successful they have been in systematically pursuing all possible solution paths.

Exploration — By providing students with a situation where they can practice and experiment doing the activity alone, they have the opportunity to actively process and come to "intuitively believe" what they have been taught.

### 3.2.2 Instructional Sequence

In addition to the supportive teaching methodologies, consideration must be given to the sequencing of instruction. The final instructional sequence will be determined by the POI and the results of our investigation on whether breath-first or a depth-first approach to tutoring is more effective. Initial instructional sequencing in the simulation will be driven by increasing problem complexity, gradual removal of instructional support, and increasing problem diversity. These are briefly described below and in greater detail in Section 3.3.

As student performance improves, the tutor gradually increases the complexity of problems. This complexity is characterized by greater conceptual difficulty, more information to recall at one time (chunking), an increase in the number of skills to perform at one time, integrating previously learned skills, and greater accuracy and speed during performance. Ideally, those previously mastered skills are continually interwoven into increasingly more complex problems, rather than set aside for later revival.

The various supports provided by the tutor through the learning process are called scaffolding or prompting. As the student's performance improves, the tutor gradually reduces the amount of prompting. This removal is called fading[6] Fading helps ensure transfer, since the student eventually has to perform the task unaided. Instructional supports should provide

[6] If this prompting is not gradually faded, it can actually distract the student from the task.

a means whereby these prompts are internalized in the student, such that when the student runs into difficulty, the student prompts himself automatically.

Another sequencing factor is increasing the diversity of problems presented. Alternative strategies and skills may be required at different times. Although it is critical to have mastered (made automatic) the strategies and skills in one particular sequence or application, the student needs a variety of situations to learn when it is appropriate to apply those skills and when it is not.

### 3.2.3 Practice

In addition to teaching methodology and sequencing, sufficient guided practice (coaching) and simple practice must be provided. Guided practice is often confused with simple practice; simple practice is a stage that follows guided practice. Simple practice assumes that the student already knows what the critical parameters of the to-be-learned skill are. It consists of repetition to make the skill automatic in accuracy and/or speed. This repetition also "shrinks" the number of steps involved in the skill into a "chunk", so that the student no longer thinks of each step as a single entity unto itself, but as one of many belonging to a functional unit.

### 3.2.4 Skill Maintenance

Learning and practicing a skill in the context where it will be applied increases the chances of recalling that skill and that the level of accuracy of that skill will be maintained. A skill that is routinely used is retained at a much higher level of accuracy than one that is infrequently used. By simulating diverse sets of troubleshooting problems that range in difficulty, critical skills and strategies can be routinely used and further expanded during the instructional interaction. To prevent forgetting a previously learned, occasionally used skill (but no less important), a student must "overlearn" the skill, i.e., practice it until it is automatically performed without conscious effort. This cannot occur at the cost of frequently needed skills. However, the MACH-III can monitor the occurence of these nonroutine skills and present a sufficient number of opportunities to maintain them.

### 3.2.5 Motivation

An intrinsically motivating (Lepper and Greene, 1978) task is one that interests the student and thus, empowers the student to learn more than they would otherwise. Interactive tasks are more intrinsically motivating than tasks that are passive, such as reading large amounts of text. Tasks which involve peer interaction, such as peer tutoring, small group problem solving, peer competition can be highly motivating. An example of a motivating task could be where one student can select a particular fault (of a particular difficulty level) to put in the simulation for another student to find. If a score-keeping method is used, this could be a competitive situation (between students) or a self-motivating one (get a better score). It could also be a highly motivating situation if the student who inserted the fault has to model the correct solution for the other student. A cooperative situation would involve a group of students, each taking responsibility for certain parts of the troubleshooting procedures - and having to justify their actions to one other to correctly locate the fault. This mirrors some of the interactions at Ft. Bliss, e.g., when one radar mechanic directs another to perform a task on the other side of the radar or when the junior mechanic cannot solve the problem and turns to a senior mechanic for advice.

### 3.2.6 Summary

In summary, our instructional approach includes several thrusts:

- o teaching the domain content from a functional point of view
- o teaching the strategies the student must have to direct and evaluate his troubleshooting actions
- o simulating problems for the student to solve which utilize his domain knowledge and strategy skills
- o presenting problems of increasing difficulty and increasing complexity
- o providing initial learning supports and fading them as the student progresses
- o using a variety of interwoven teaching methods to help the student internalize the knowledge and problem-solving skills necessary for effective troubleshooting
- o providing a sufficient amount of practice to initially grasp, achieve fluency, and maintain skills and strategies
- o providing intrinsically motivating situations that empower students to learn

## 3.3 Modes of Operation

The simulation will operate in a number of modes simultaneously, depending on the student's requests, performance and the level of problem difficulty. For discussion simplicity, the simulation's operations will be divided into two general modes: tutor-student interaction and levels of problem difficulty.

### 3.3.1 Tutor-Student Interaction

The tutor-student interaction mode contains the six instructional elements described in the section under "Instructional Methods": modelling, coaching, inquiry, articulation, reflection, and exploration. While these are individual elements, they may be knit together in different ways under different conditions, depending on the mode of interaction (as selected by the student) and the student's actions. For example, if the student requests an expert's solution of a problem, the simulation describes the problem, explains what issues were considered, and models the steps for locating the fault. In the exploration ("solo") mode, if the student fails to locate the fault, he may request "hints" from the coach, and receive help in increasingly more specific detail. If a student selects "teaching examples", he selects the coaching mode and is guided through the problem-solving process, where the simulation explains, questions, assures, and corrects the student. The six modes are not necessarily orthogonal to one another: the student could ask for the expert's solution for the problem given in the exploration mode, or the student could "turn off" the coach in the "example problem mode" when he (the student) thinks he has the answer.

Another mode relevant to the tutor-student interaction can be described as "summary" mode that is specific to the functional area of the problem, such as the receiver. This would contain a brief, high-level description of that area's function, possible areas of breakdown (and which are more likely), and possible tests to perform (and their purpose). This mode is useful for hierarchically organizing the student's knowledge upon initial introduction to the area or if he becomes lost in the details of problem solving.

### 3.3.2 Levels of Problem Difficulty

Troubleshooting problems in the simulation will be organized according to their complexity and how well they contribute to basic system understanding. Levels of problem difficulty entail three overlapping aspects: how difficult the fault is to locate, how difficult the functional principle is to grasp, and the number of procedural steps involved. Problem selection will carefully control these three aspects to avoid inducing cognitive overload. For example, when introducing a conceptually difficult concept, the procedural parameters will be kept simple, and the fault will be easy to locate. Similarly, when the fault is difficult to locate, only familiar concepts and simple procedures will be involved until the student is ready to attempt a more difficult problem.

Fault location is described in the next section below. The next section on Views discusses both the functional and procedural aspects of problem difficulty, since these are difficult to discuss separately.

#### 3.3.2.1 Fault Location

The ease with which faults can be located partially depends upon the amount of circuit tracing (in the schematics) involved and whether or not a functional feedback loop is involved. Fault location within each functional area will be introduced in the order described below:

1. Fault Location via BITE Tests (No Tracing): The overall system BITE (Built-In Test Equipment) and the specific system BITE (e.g., TCU, SCU, DSP) tests indicate problem components by not lighting up the lamp associated with those components. When the problem is, in fact, the indicated component, the student simply directs the simulation to replace the faulty module or repair it (as in reconnecting a loose wire). This is the simplest case of problem solving.

2. Simple Circuit Tracing[7]: If the problem indicates a problem that is not the actual component indicated by the overall or specific BITE test, the student must track down the source of the faulty input. The source can be within a few components' distance (not necessarily physically close, which is easier) or it can be many components away. Simple circuit-tracing problems involve sequentially checking or replacing the few (say, less than four) components between the indicated component and the actual faulty source input. The student can then trace the circuit by going forward (toward card 5), backward (back to card 4), or in some other order. While the student directs the simulation to perform testing/replacing actions, it can visually display the order and results of those actions, eliminating potential cognitive overload. Thus, the student actively practices the reasoning process and receives a visual summary of his performance. This visual summary is vehicle by which the student can compare his actions to that of an ideal or save the summary as a future reference.

3. Complex Tracing and Functional Loops: After the student can track down a fault through simple circuit tracing, s/he will have to track down faults that are many components away or that are involved in functional loops. When many components are involved, the student needs to select strategies that reduce the possible search space, such as a binary search (halving the number components involved, then halving again, and so on).

   To troubleshoot a functional loop, the student must first determine which functional loop is involved, and then track down the components involved in that functional loop (a type of circuit tracing). Since a functional loop often involves many components which act together as a single, higher-order unit, all the components' inputs are essentially all faulty. (This is analogous to a derailed bicycle chain, where one derailed link impairs the function of all the links). This is a difficult task in and of itself; furthermore, some functional loops contain other loops, which all act together more or less instanenously, rather than sequentially. This concept is extremely hard to grasp, and is, thus, difficult to troubleshoot in a logical fashion. In addition to the visual summary of the student's actions, a simple sketch of the functional loop which includes the relevant components and signal information, would provide the student with a conceptual framework from which to troubleshoot.

[7] N.B. The term "circuit-tracing", which generally connotes electrical connections, has been extended to include components on the sequential "path"; these components may involve other "energy" forms, such as electro-mechanical, mechanical, and RF (microwave).

### 3.3.2.2 Views - Functional and Procedural Knowledge

This section describes the level of problem complexity with respect to the amount of detailed system (functional) knowledge required and number of procedural steps involved when troubleshooting.

When the student interacts with the simulation, he will see three types of display views:

1. Overall Functional View: involves a very high level functional overview BETWEEN the five subsystems comprising the radar. It generally shows what each subsystem's major inputs and outputs are in relation to one another. See Figure 3-1 for an illustration of this view.

2. Subsystem Functional Views displays a functional overview WITHIN each of the five subsystems. It shows the major functional components of the particular subsystem, and the inputs and outputs between its components. Figure 3-2 shows a functional view of Receiver subsystem and the functional components which comprise it.

3. Physical Components View displays the functional subsystem view and the actual physical components which comprise those functions. Each of the five physical views also displays which components are contained within the replaceable modules and which are not. Accessible and internal connections are also illustrated. Figure 3-3 is an example of the physical component view for the Receiver subsystem.

The student will begin with the Functional Overview, progress to the Functional Subsystem Views, and eventually learn the physical components attached to the subsystem functions through the Physical Components View. (Studies will be conducted to determine whether students should progress from a functional subsystem down to its individual physical components ("in-depth" approach) before attempting another subsystem or whether they should master all of the subsystems at a functional level prior to attempting any of the physical components levels ("breadth" approach.)

For each of the three views, students will always have to solve problems relevant to the displayed components. The simulation always will provide a description of the symptoms for the presented problem. The simulation of each view will be "runnable" and replacement of the viewed components possible. Thus, the student will always have problems, however simple or complex, to solve in context. For each problem, he must proceed through certain stages: he must understand and verify the symptoms, form a hypothesis based on his system knowledge, select components for testing, isolate the problem source and recommend the replacement of a certain component. The system will provide, at each level, learning supports in the form of demonstration, coaching, and systematic inquiry. Students can make their intentions known (articulate) by selecting from a menu of reasons and actions.[8] The system

[8] These menu options will be limited to prevent random actions. Examples of these options may include "test this component", "measure the voltage here", "replace this component", "push system BITE", etc. However, "I don't know" and "none of the above" will be included to indicate puzzlement and disagreement with the provided options.

# Simplified HIPIR Block Diagram

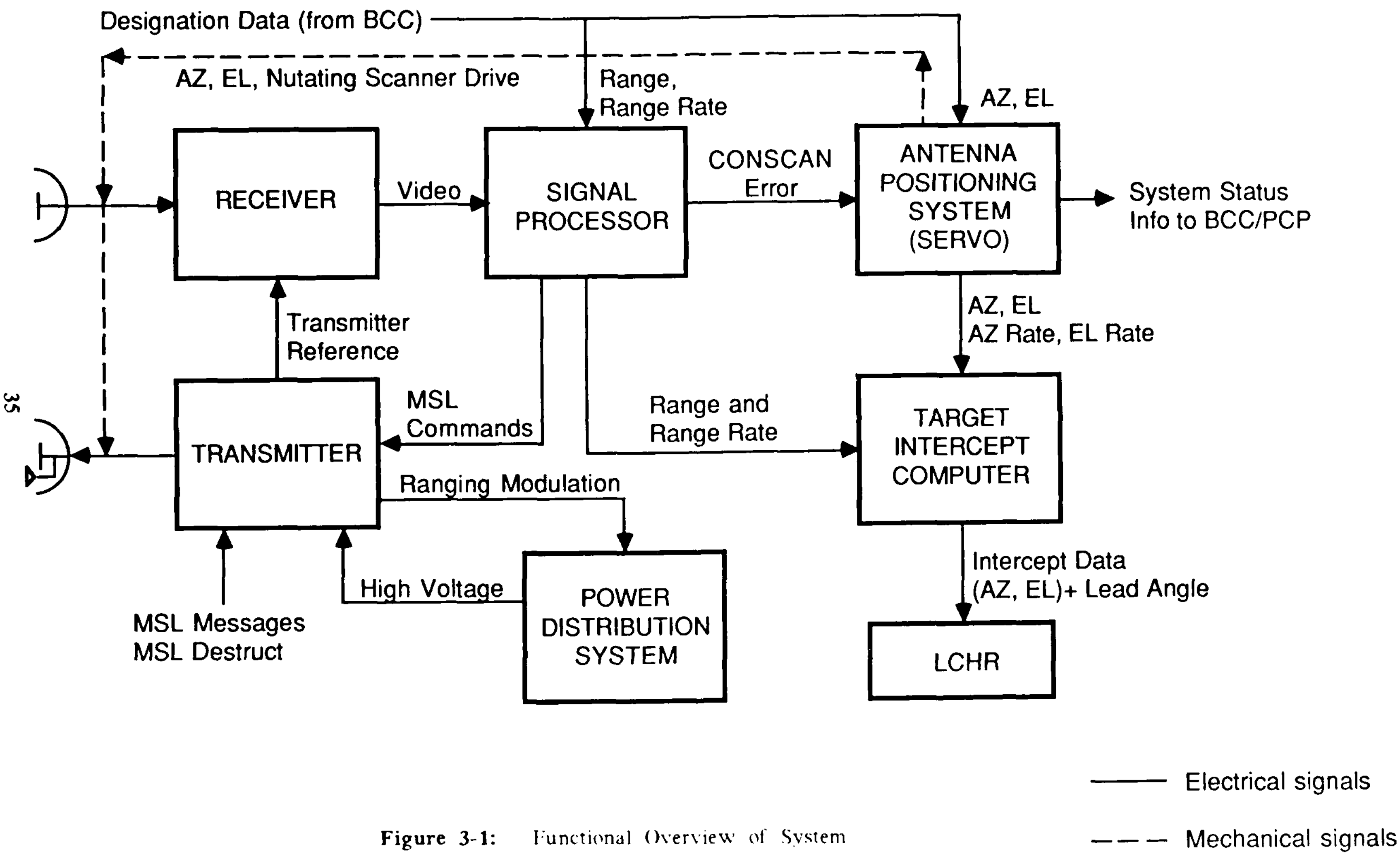


**Figure 3-1:** Functional Overview of System

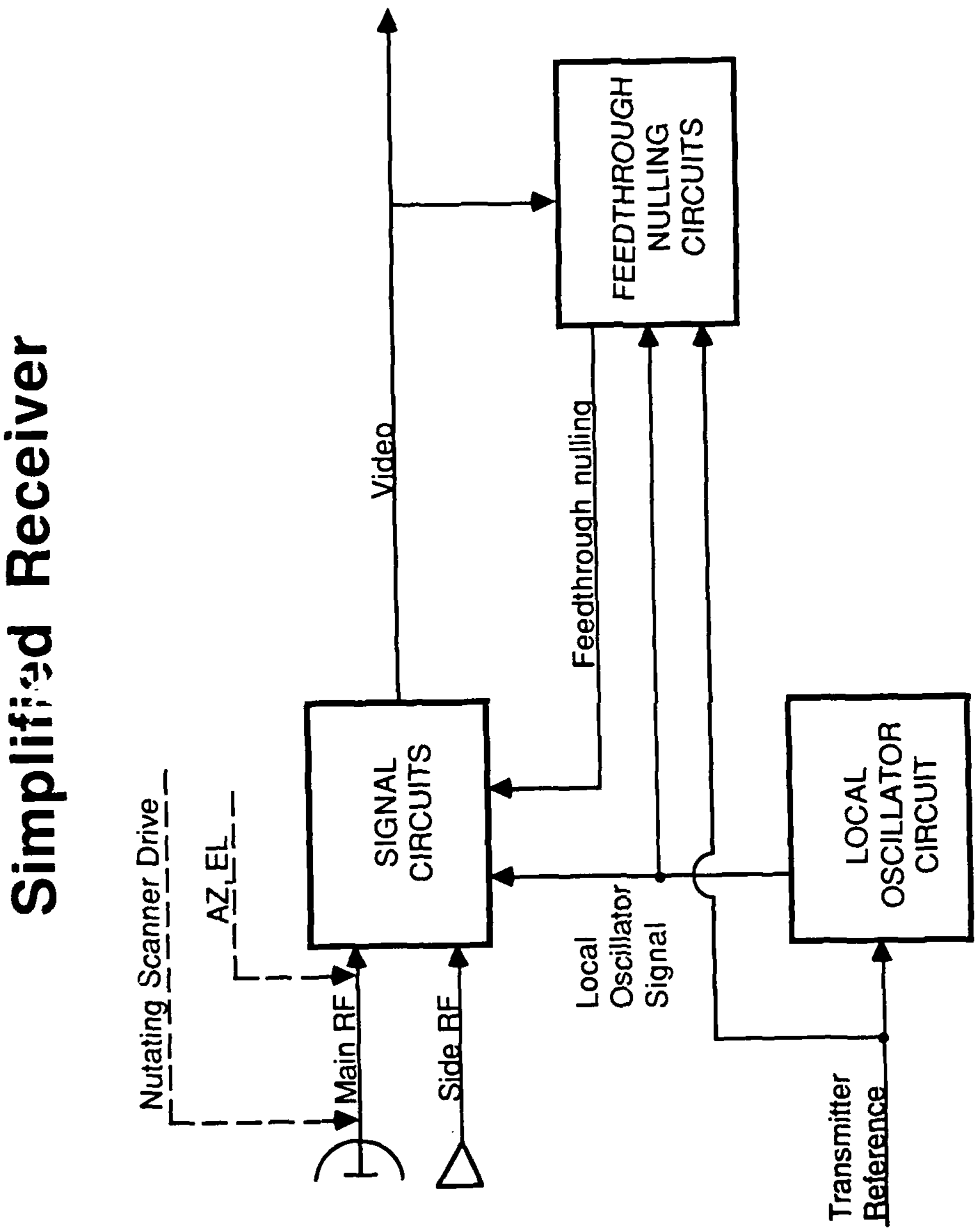


**Figure 3-2:** Functional View of Receiver

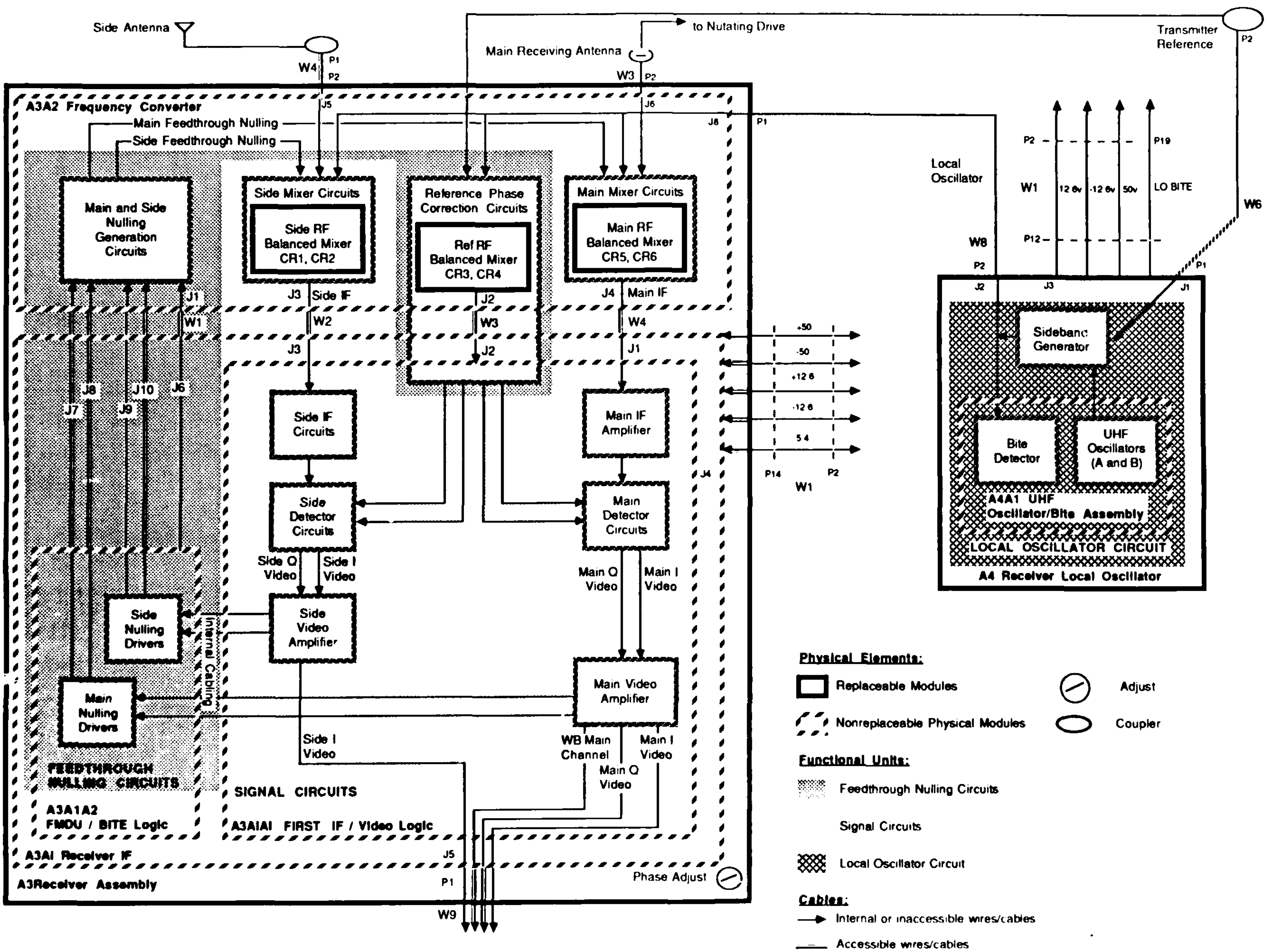


**Figure 3-3:** Physical Components of Receiver

will also provide visual feedback to compare the student's performance against a more optimal one. Debriefing in the form of a "replay mode" of the student's solution approach to a more ideal approach will be provided after a student's solo (unaided) problem-solving session. Finally, an exploration mode will be provided where students can practice and experiment.

Within each view, problems will range in complexity and diversity. The number of possible actions will increase along with the amount of knowledge the student must utilize to solve these problems. As the student progresses, tests and their results will become increasingly more specific to components and open to the student's interpretation. For example, a simple test result may indicate "normal" function; later the same test may indicate "normal - ranges between 10 and 12 volts". Still later, when the student requests a test, the system may ask "what equipment?" and provide a menu of relevant equipment options. The student will have to select the "voltmeter" option, read the simulated voltmeter, and decide whether the indicated "20 volts" is within the normal range or not.

What will change across the three view types will be the increasing amount of specific knowledge required about the components in the displays (there will be more components). The number and implementation of the student-selected tests will also vary, particularly with the Physical Component View.

At the easiest levels, students will be provided with specific informative symptoms, a small number of hypothetical possibilities to investigate, and very few tasks to implement and coordinate. Essentially, the student's rudimentary system knowledge and strategy skills will be utilized in isolating the source of the problem. "Functional test" results can be requested as to whether a component is working; when performing the functional test, the student does not actually implement the test procedures, but only receives the results of that test. This functional test provides the student with the means to test his hypothesis by collecting the relevant data without burdening him with the test implementation details. Based on those results, he then has to decide what to do next with his hypothesis. This functional testing provides practice in good hypothesis formation and systematic test strategies at an early stage, making systematic implementation of more detailed test procedures more likely.

At the most difficult levels, students will be given vague symptoms (e.g., "the radar doesn't work"). Problems will involve external devices as well as the internal components of the HIPIR. They will have to ascertain and verify the symptomatic characteristics of the fault themselves prior to pursuing any hypothetical solution paths. Simulated equipment such as voltmeters or the system-specific BITE will yield the appropriate responses. The student must fully implement the test procedures (as adapted to the simulation) to obtain any desired results. Interpretation of the data is the student's responsibility, as are the (simulation adapted) procedures for replacing the simulated modules. Eventually the student will have to solve the problems alone without a timed component. Later, time limitations will be added, since the 24C MOS must troubleshoot at the TAC site under time constraints. At this level, students are totally immersed with all facets of troubleshooting problems.

The intermediate levels pertain to the inclusion of two major (cognitively heavy) tasks: (1). the gradual expansion of the functional components to include the physical components and (2). the implementation of the specific test procedures. Both of these two tasks have the potential to overwhelm the student with details, and thus, have been separated into two stages of instruction.

During first intermediate level, each of the functional components within the functional subsystem view can be "opened up" when selected with the mouse. It is important to ensure that the student's functional model be tied to the layout of the physical components. Although it is critical that the student have the correct functional understanding (mental model) of each subsystem, their components and the interrelationships between them, students must, in the end, know where and what to measure, remove, replace and adjust[9]. Since it is easy to lose students in the transposition of that functional model to the actual radar, this first intermediate level has been incorporated into the situation to ease this transition. Utilizing his functional knowledge and strategies, the student can now isolate faults to individual physical components. The tests, however, are still functional tests, i.e., the individual test steps are not implemented by the student. Instead, the computer provide the results of a specifically requested test and the student must interpret what those results mean.

At the second intermediate level, the individual steps of the test procedures must be implemented by the student. What differentiates this second intermediate level from the difficult level is the amount of help and problem difficulty. To offload the cognitive demand of implementing the procedural steps, very simple problems will be given. Substantial practice of procedural implementation is critical at this stage to encourage "chunking" of the individual procedural steps into a single procedure in the student's mind.

## 3.4 Relationship to the POI

While the MACH-III trainer will address the acquisition of an accurate mental model of the HIPIR's function and operation and provide the cognitive foundation for troubleshooting strategies and skills, this cannot be totally independent of the current POI. From our observations and from HAWK personnel commentary, a revision of the current documentation is desirable, but is beyond the scope and capabilities of this project. However, with respect to the MACH-III instruction, documentation pertaining to any instructional information or visual displays presented therein will certainly be provided. These may be used as a supplementary materials in concert with the current materials.

Upon the conclusion of this project, the sequencing of the MACH-III instruction and the POI, will be coordinated in parallel. Prior to a MACH-III prototype, student interviews will be conducted to ascertain where conceptual misunderstandings occur. These will be evaluated with regard to whether the MACH-III can incorporate these areas into the instruction. During development, research will be conducted into the optimal MACH-III instructional sequence for students and how well it will mesh with the current POI. A reasonable first attempt is to follow the current sequence, i.e., when the students cover a particular system in their classes, allow them access to that particular system on the MACH-III. Instructor and student

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[9]However, the physical layout of the radar does not always lend itself to neatly co-located functional groups. It is quite possible that a functional box called "widget signal processing circuits" is physically dispersed in several places within the radar and connected by numerous cables, each labeled with nine alphanumeric characters. The simulation should give the student an idea of the physical representation of a functional component, but suppress the overwhelming details irrelevant to troubleshooting procedures.

evaluations regarding the impact of the MACH-III on the POI will be gathered in concert with student performance on the MACH-III system and in the 24C course. As the ongoing formative evaluation continues, the sequence of instruction between the POI and MACH-III will be shaped according to the results, until an optimal order is attained.

### 3.5 Instructor Authoring

Authoring capability for instructors is important for keeping the current instruction up to date and for amending particular sequences which have shown a need for revision. A sufficiently flexible interface must be between the system and the instructors. The functions of this interface will be developed following an evaluation of what functions are needed, what kind of instructional or interface revisions need to be made, and how extensive these revisions are. Additionally, the future authors need to have an functional understanding of what it means to author and how to implement this process effectively.

### 3.6 Record Management

Although the computer is quite capable of keeping records of student performance as measured by number scores, this in itself, it not always instructionally informative. It does not always provide the full flavor of how the student solved the problem, only that they did or did not succeed in doing so. It remains to be determined whether the "replay" mode is an effective means of preserving the problem solving proceedings, and whether the instructors would find this useful or desirable.

In addition to a correct percentage score, other measures may be useful, such as time to completion (and thus, rate of completion), number of hints requested, number of coaching interventions performed, rate of improvement (slope on a graph), consistency of performance and level of maintenance (amount of variability between scores on a graph). These measures could be monitored for each problem in each functional area and/or in total. These measures (or a subset of them) may displayed to the student and/or just the instructor, or these may only be used for internal criteria for the simulation to determine when the student is "ready" to move on to another level of difficulty.

## 4. TARGET POPULATION

This chapter presents an overview of how MACH-III will be used at USAADASCH. The sections of this chapter describe how the demonstrator will be integrated with the current POI (lecture, CAI, simulators, and real equipment), which tasks it will support, how soldiers will use it, how instructors will use it, and what potential it may have for expansion to other HAWK tasks and other systems.

### 4.1 Integration With the POI

The development and integration of MACH-III into the HIPIR training program involves two populations--the USAADASCH instructional staff and the 24C trainees.

Several major tasks which directly involve the instructional staff are required to successfully develop the MACH-III program. These tasks require that a collegial atmosphere be established between the staff and the development team and that the different facets of the overall task be clearly understood. This involves:

- o an understanding and agreement upon the educational philosophy (mental models, guided practice) driving the instructional side of the system, and

- o the technical potential and limitations of the MACH-III program

On the educational side, specific issues must be addressed and their impact on the current curriculum assessed:

- o definition of and agreement upon the important instructional topics and concepts,

- o organization of those topics into levels of a functional hierarchy (as previously addressed in the cognitive section of this report), and

- o instructional delivery of those topics, such as the man-machine interface and the "sticky points" which need extra emphasis in the courseware.

On the technical side of MACH-III, the USAADASCH instructional staff primarily needs:

- o to be informed of potential and capabilities of computers in general (underlying fears of "being replaced" by a computer--which have been expressed--need to be alleviated);

- o to be informed of what an "intelligent system" can and cannot do, how it works, how it is different from traditional CAI and other instructional methods, its advantages and disadvantages, and its potential uses as an instructional tool;

- o to be informed about the MACH-III system and discourse domains, the potential authoring capabilities, and the methods of instructional delivery;

- o to inform the development staff about the requirements of current instructional and administrative paper work; and

- o to inform the development staff about other student information which may help train more effective troubleshooters.

Once the educational and technical directions have been addressed and emerging prototypes of the MACH-III system are developed through formative research, the development staff and the instructional staff can evaluate the impact of the system on the present curriculum. Together, they will determine which instructional activities reed to be modified or alleviated and if necessary, how the curriculum should be restructured to accommodate the changes made by the MACH-III.

In particular, because of the articulate, guided, "hands-on" aspects of the instruction, the varying levels of troubleshooting tasks, and the immediacy of feedback, students may have qualitatively different practice session(s) from the current practical exercise (PE) session. Whether new session(s) must be scheduled in addition to or can replace the current PEs or other scheduled curriculum events, such as exams, is difficult to determine until the prototype's impact can be assessed.

The curriculum will have to include an introductory session to briefly familiarize the student with the physical configuration of the MACH-III system and its interface. Provisions for student interaction with MACH-III must be woven into the curriculum; the impact of this scheduling must be coordinated with the POI and the remaining time available in the 24C's schedule.

The ease of access to the MACH-III (with or without instructor supervision) will constrained by administrative policies at Fort Bliss. The possibility exists that students may have open access to the MACH-III, since it is not dangerous to use like the radar. Therefore, at the student's instigation, pursuit of extra practice or deeper understanding of the curriculum material could be an available option. One potential activity, such as a student setting up problems for another student to solve, increases motivation and provides additional modelling of how to problem solve, as shown by the peer-tutoring literature (Jenkins *et al.*, 1984). These activities could be included as part of the curricul m or made an optional activity. Whether this scenario is possible will depend on how difficult the feature is to implement and, if it is, whether the feature is used by the students.

Another potentially useful feature allows a student to request extra problems on selected areas. For example, a student may request more problems to solve on the antenna positioning system because s/he still feels shaky on it, even though s/he performed correctly. If this feature can be implemented, it would be very interesting to monitor the frequency of these extra sessions or requested activities and their effect on the student's performance.

The curriculum materials themselves would have to reflect the visual displays provided by the MACH-III. Because of the ephemeral quality of the computer medium, reinforcement of the cognitive models presented by the MACH-III would be helpful. It is likely that the student may recall the vital information was in the right hand corner of a particular functional screen display, but cannot recall th exact nature of it. Having the same diagram on paper to peruse at another time and place would not only promote understanding and transfer, but also allow the student to make notes on the relevant components.

A means to assess how well the knowledge acquired througn the MACH-III system transfers to the real system will have to be constructed. During development, results from this ongoing evaluation will be incorporated into the system and/or the curriculum to facilitate this transfer. Factors which influence the transfer will be determined and addressed via a specific instructional mode or via a combination of modes. This will entail assessing several groups of students in their system model, and their specific curriculum knowledge before, during and after their instructional course.

Factors contributing to this transfer will be evaluated prior to evaluating the effect of the instruction. Such factors include the student's background knowledge of the subject, educational background, employment experiences, general range of ability, motivation, quantitative and qualitative abilities, ASVAB scores, and possibly, their problem-solving ability as demonstrated on standard tests.

## 4.2 Trainee Interface

The instructional content, as previously described in the cognitive section of this document, will present a mental model of the HIPIR which allows the student to "plug in" increasingly specific and more complex information about the system. The MACH-III simulation will be the physical manifestation of this cognitive framework.

The system functions will be presented at three levels (as described in section 3.3)-- *subsystem*, *functional*, and *replaceable module*. The *subsystem* level pertains to the major parts of the HIPIR and their interrelationships. The *functional* specifics of each of these subsystems will be expanded and demonstrated. At the *replaceable module* level, the actual physical subassemblies comprising these functional components will be displayed to the student. When the student is deemed ready (depending on research results), s/he will be able to move from the *subsystem* presentation into the *functional* and *replaceable module* presentations. This traversal will be directed through the interface by "selecting" (via keyboard or mouse) to expand or contract the amount of detail in the current view.

The instructional purpose of the *subsystem* level is to demonstrate the overall operation of the HIPIR, its relationship to the various parts of the air defense mission and system, and to illustrate faults which affect overall HAWK system operation.

The instructional purpose of the *functional* level is to illustrate the operation of subsystems of the HIPIR, their relationship to overall radar function, and to illustrate how faults in particular functional areas generate erroneous signals which propagate malfunction to other HIPIR functions and result in identifiable patterns of malfunction.

The instructional purpose of the *replaceable module* level is to provide a basis for demonstrating the troubleshooting process as it applies to the organizationally maintainable parts of the HIPIR. This level is specifically intended to demonstrate the roles of physical devices in radar function, as well as the roles of supporting equipment such as cables and power supplies. This level also shows how faulty parts generate faulty signals and how faulty signals can cause non-faulty parts to malfunction.

Some elementary troubleshooting will be demonstrable at the *subsystem* and *functional* levels; this will be of a general nature. Detailed troubleshooting exercises will be provided at the *replaceable module* level.

The MACH-III will contain a function which controls the presentation of material at each of these levels, based on information incorporated in a student model. This function is called the *curriculum director*. Information for the student model will be elicited by direct prompting of the student with multiple choice questions about intention and knowledge (e.g., "What do you hope to learn by that test?", "What can you conclude about ... at this time?"). (This system function will be developed based on the research results as to whether the presentation should go across ("breadth") subsystems first or within a subsystem ("depth") or some combination.)

The articulate expert troubleshooter will present content material visually on the screen as text and may present some material aurally via a speech synthesizer. Presentation mode will be partially determined by the required task itself - if the student is supposed to be watching a demonstration, the graphics will show what is to be observed while the expert describes the action aloud. In some portions of the instructional sequence, the mode of presentation will be selectable by the student, particularly if the sequence has been seen before. Speech is slower and potentially aggravating to hear over and over. Conversely, students who do not read well should not be hampered from comprehending the system's inner workings.

A number of other issues will need to be resolved in development of the trainee interface. These include issues of how overtly the system should provide meta-cognitive information about the instructional process, that are not directly related to the content of the instruction itself, such as:

- o The location of the student's current focus in the system simulation, and
- o The parts of the curriculum lesson mastered, not mastered, and not seen yet.

## 4.3 Instructor Interface

Once the kind of information needed by the instructor has been identified and methods developed for its acquisition, the format and presentation mode (e.g., display, hardcopy) of these records should be selectable by the instructor.

The instructors will be able to see the various instructional modules and exercises, a student's progress through them, the student's cognitive deficiencies and the system's prescription. The instructor will be able to override the instructional prescription by recommending that the system present the student with alternative material, repeat material already presented, or skip ahead to new material.

## 4.4 Technology Transfer

An authoring assistant function will be prototyped as a part of MACH-III late in the development cycle. This function will provide mechanisms by which instructors and/or courseware authors can develop new instructional task material using the MACH-III's knowledge manipulation procedures. (This same facility will permit instructors to fine-tune the instructional strategies pursued by the MACH-III demonstration.)

Future authors will need to become familiar with the requirements and limitations of symbolic hierarchical models of complex systems, as implemented by MACH-III. They will also need to understand the method chosen for representation of system-specific troubleshooting knowledge and the relationship between the instructional strategy knowledge base (including system-specific aspects of the student model) and the instructional behavior of the MACH-III.

We believe we are developing a concept for hierarchical symbolic simulation of complex systems which is fully extensible to modeling the normal and faulted behavior of many systems other than the HAWK HIPIR. Our modeling technique emphasizes the transformative action of faulty and/or non-faulty system modules on faulty and/or non-faulty internal system signals, as such action is defined by rules of symbolic transformation on signal name, identity, and character. This technique of representation is fully generalizable to a wide range of systems which share certain operational, structural, and organizational maintenance features with the HIPIR.

While the process of analysis which must be applied to an existing system may at first appear complex and abstruse, we have now explored several parts of the HIPIR and believe:

1. There is no unique characteristic of the HIPIR on which the operation of this approach depends, and

2. The analytical process is actually quite methodical and can be taught to people with a normally complete operational/functional knowledge of the target system.

In the same way, we are beginning to feel that, so long as the target system is organizationally maintained using a practical doctrine for application of the detailed knowledge of relevant TM's and expert experience which is similar to that used for the HIPIR, adaptation of the troubleshooting expert to a new system application should be possible with minimal actual reprogramming.

Finally, we believe an effective instructional strategy for HIPIR training administered by the MACH-III will employ the same concepts and methods as an effective instructional strategy for MACH-III training for any other complex system.

Therefore, we conclude that the MACH-III technology should be highly transferable, largely by trained subject matter experts, to the training of equivalent practical operational and organizational troubleshooting concepts and skills for any other similar complex system.

# 5. DEVELOPMENT PLAN

This chapter describes the tools, procedures, and methods we plan to use in developing the MACH-III demonstrator. In this presentation the techniques discussed in chapter 2 and the capabilities described in chapter 3 have been combined and analyzed to yield a technical design of the intelligent tutoring system to be built for MACH-III. Development activities are discussed from the viewpoint of cognitive science, instructional design, artificial intelligence, subject matter, and system integration.

## 5.1 Cognitive Science Development

We will need to collect data at USAADASCH at different points in the project. At the outset, we will need to work with experts to determine how they think about the functioning of the system at various levels of specificity. The information gathered from these interviews will be used to validate the proposed hierarchy of models to be simulated on the trainer. It will also play a role in determining the kinds of explanations that will be generated by the system.

Information about the experts' model of the system will be obtained in the following manner. First, a number of experts will be asked to describe how the radar works, using any diagrams they find helpful. Next, they will be asked to describe the functioning of the system by drawing boxes to represent parts and arrows to represent the functional relationships between them. To probe for a more general representation, they will be asked to combine any boxes that can be combined and redraw the arrows. To obtain more fine-grained explanations, they will be asked to break each box into its components and indicate the interconnections . Questioning will proceed in this manner until the subject indicates that components cannot be broken down or combined further. Finally, we will present the preliminary set of hierarchical models that we have worked out, with the arrows deleted. The expert's task will be to fill in the arrows and explain the connections. These procedures, which have been used successfully by the LRDC group at the University of Pittsburgh, should give us a good idea of the expert's model of how the system works.

Secondly, we will need to work with the experts to become familiar with the kinds of troubleshooting problems that are encountered on the job and the procedures that are actually used by the experts to to solve these problems. This information will be used in deciding what skills are to be taught. More specifically, it will help us to design problems and demonstrate solutions in such a way that the student can acquire some of the skills of the expert.

Several techniques developed at LRDC will be used in this phase of the research. First, experts will be asked to define the problem space by providing examples of troubleshooting problems at various levels of difficulty. They will be asked to discuss why the problems are difficult or easy. Next, troubleshooting protocols will be obtained by asking two experts to pose hypothetical troubleshooting problems for each other. They will be asked to describe a symptom and then answer questions about specific test results until their partner has determined the fault. In preparing their problem, the experts will be asked to anticipate possible tests and meter readings that their partner may propose and come prepared with the required information. The experimenter will ask questions of the troubleshooter at appropriate points (e.g., What do you hope to learn from this test? What do the results of this test tell you?).

This procedure, which takes place away from the actual equipment,has several advantages. First, it allows for the troubleshooting of hypothetical faults that, for practical reasons, could not easily be "planted" in the radar. Secondly, it requires the troubleshooter to verbalize proposed tests, making each step in the procedure explicit. A possible disadvantage of this method is that the troubleshooter does not have the visual support of the radar. Steps that are performed automatically in the context of the radar may be forgotten when the problem is presented hypothetically. This potential disadvantage has not proved to be a problem in other research. However, we may observe some on site troubleshooting as well.

Once the simulation of the HIPIR at a hierarchy of levels is complete, we will want to work with students at USAADASCH to compare the efficacy of different teaching strategies. First, we will want to check our assumption that exposure to a series of increasingly specific models is helpful to the student in acquiring a detailed model of the system. Students who are introduced to the radar, one level at a time, will be compared with students who spend all their time working at the most specific level.

Secondly, the availability of a hierarchical simulation will allow us to explore the optimal order for introducing students to the material. In particular, we will contrast a breadth-first approach, in which students are given information about the whole system, one level at a time, with a depth-first approach, in which students are taught about one component in depth, before moving to the next component. The optimal strategy may prove to be a combination of the two, e.g., going through the system one level at a time at first and then going back through the system and tracing each part through all of its levels.

These teaching issues will be explored in pilot studies, using small groups of students. If time permits, a more extensive study of optimal presentation strategies may be undertaken.

## 5.2 Instructional Development

Interviews will be conducted with a range of maintenance mechanics, platform ("hands on") instructors, and students to ascertain what areas in the instructional program were helpful and not so helpful for troubleshooting the radar. The subjects will be asked to describe other relevant subject areas, electronics background, training experiences, or methods not covered by the HAWK POI that they thought were critical to good troubleshooting and/or contributed to their general understanding of how the radar works.

Of particular interest are relationships between the perceived value of the basic electronics course, the extent to which the subject comprehends the electronics domain, the subject's mental model of how the radar system functions, and how well the interviewee can troubleshoot - on the radar itself and "on paper". These relationships will be used to establish an approximation of the interviewee's electronics knowledge, and radar and troubleshooting expertise.

Another source of information for instructional development will come from interviews with a small number of current students (ranging in ability as determined by an instructor), after each subsystem in the HAWK HIPIR course is covered. From these interviews, not only will their general grasp of the material be ascertained, but their evaluation of the instructional material and of their own performance will also be elicited. The students' evaluation of the course may provide insight into:

- o their misconceptions about the information presented and its purpose
- o what areas or concepts were particularly difficult for them to grasp, and how, if ever, did they finally come understand them
- o their general level of motivation (i.e., what was interesting) and what increased or decreased that motivation
- o what information was particularly helpful in learning to troubleshoot that subsystem and the overall system

Interviews with the maintenance personnel will cover the same areas as with the current students above, but other questions will be asked of them as well:

- o If they have been to the operational TAC site, they will be asked whether the kinds of problems they encountered there were different from the ones at the school; if so, they will be asked to describe those types of problems and how often they occurred
- o How often, when, and with what type of problem they currently use the FIP, the schematics, and other documentation; how they would change the documentation - its weaknesses and strengths
- o They will be asked to describe their troubleshooting methods, both on the job and on the TAC site, for particular types of problems (including shortcuts), and how they know when to use one method as opposed to another
- o They will be asked to describe and demonstrate how they would teach troubleshooting to an inexperienced mechanic who is fresh out of school and to contrast this with how they were taught to troubleshoot in school - what they would emphasize or deemphasize in the practical exercises, and what are useful shortcuts to take or additional checks to make the troubleshooting faster and more informative

The results of these interviews, together with an analysis of the POI and the content of the practical exercises, will yield a basis for focusing development of the MACH-III simulation and incorporating it into the current POI.

## 5.3 Artificial Intelligence

In Section 2.2 we argued that, in our view, a troubleshooting tutor needs to provide a student with more than just a set of examples of correct troubleshooting. The tutor should also be able to explain the reasoning behind those examples, allow the students to try troubleshooting themselves, and provide them with adequate feedback. In addition to this, the system should contain a simulator to allow the student practice in operating the device and learning its behavior by actually manipulating its parameters. As was argued in section 2.2, there are major disadvantages to keeping the simulation completely distinct from the qualitative knowledge needed to generate explanations. Therefore we will build an expert mental model of the HIPIR, i.e. a simulation in symbolic, causal terms reflecting the way an expert would explain its workings to a student.

The problem is that, in addition to the mental model of the correctly functioning HIPIR, there are as many mental models as there are faulty modes of the HIPIR. Section 2.2. discussed research that attempts to deal with this by designing reasoning mechanisms for deducing behavior from structure (and reversely deducing structure from behavior) in a very general way. This is an effort that has only begun and it seems too early to try to apply these ideas to a system as diverse and complex as the HIPIR. Therefore, we will pursue a more pragmatic approach, taking advantage of the fact that we are dealing with one particular device, about which exists a lot of specific knowledge concerning ways in which it tends to break and efficient methods for troubleshooting it.

The following subsections discuss developments to be undertaken in the AI area in support of the MACH-III. Significant work will be required in the representation of troubleshooting knowledge and in the development of the hierarchical symbolic simulation system.

### 5.3.1 Troubleshooting Knowledge

There does not exist one approach to troubleshooting the HAWK. Instead it involves a number of different strategies. As pointed out in appendix A, there first of all exist a number of problems that are very specific to the HAWK and its particular site. Checking for these specific problems seems to a matter of rather straightforward applying symptom-fault rules (although there obviously exists an explanation for their applicability--i.e. it can be explained why certain climates cause a lot of condensation and how this water can actually bring about the arcing, short or whatever.)

A second skill required for effective troubleshooting is the application of (daily and weekly) check procedures and recognition of the various indications these can yield. Finding the right procedure to perform in case of a particular indication is rather straightforward (it is indicated in the check procedure) and involves either an adjustment or a module replacement. Adjustment involves a skill that should preferably be taught by letting the student perform it on the actual HIPIR. Prior to that experience however, it will be useful to let the student practice on a simulation of (the relevant aspects of) the HIPIR. This simulation should be knowledgeable about the interdependencies that have to be taken into account when making certain adjustments. A specific adjustment expert should be able to recognize common errors and misconceptions occurring in this area.

Problems with the power supplies involve the kind of troubleshooting taught in QUEST: use schematics to trace paths of power/current, using strategies such as split-half, augmented with device-specific heuristics that take into account the likelihood of a particular component being faulty and the cost of actually checking certain modules or paths. Problems with the circuitry on the various boards (signal processing problems) call upon systematic methods for exchanging boards.

The general problem however, is to learn to make full use of the large amount of troubleshooting knowledge written down in the FIP's, without getting lost. FIP's are, in a sense, a full specification of a troubleshooting expert, presented as a huge flowchart containing many paths with redundant steps, leaving it to the troubleshooter to decide whether a particular test was already done in an earlier phase (and is still valid). In addition, all information about the strategies being followed has been suppressed in the interest of "simplicity" and "clarity". Assuming that our goal is not to replace the FIP's with "internal memory", nor to propose improvements and additions to them, it will have to be: teach the students how the maintain/repair the HIPIR using the FIP's.

The first step towards this goal will be a simulation that allows instructors to implement various modes (correct and faulty) of radar behavior and that can answer the questions students would have to ask either by deduction, convention, or because the FIP tells them so. As said before, it will not be possible to have the system derive its behavior from knowledge about the components and their connections. Therefore we will develop what amounts to a very high programming language for specifying HIPIR modes of behavior (with a view towards generalizing this language to handle a broad range of devices). This language will fit quite naturally in the object-oriented programming paradigm: devices and their components will be represented as objects that know their connections, their components, their parent modules, how to deal with certain signals in each of their possible states, how to present themselves, how to answer questions (measurements) about them.

Coaching the student while troubleshooting will be difficult. It should not be too hard to represent general troubleshooting strategies and write examples that use those strategies and include the right pointers to the FIP. However, to have a general coach capable of critiquing the troubleshooting efforts of a student would mean to have a system that either incorporates the FIP or knows how to read its instructions. Both seem out of the question. What we can do, is to develop a second language, this one allowing the instructor to easily specify the FIP procedure for this particular fault. Just as specifying components and their behavior can only be feasible for instructors if they can do this in terms of pre-specified general types of components, so will the usefulness of this FIP-language depend on the amount of general FIP strategies (such as how to troubleshoot a feedback loop) that can be taken as known to the system already.

### 5.3.2 Simulation Development

The notion of a "Hierarchical Simulation" model that we have presented is novel. There are three areas of its development that will require significant background research. First is the question of the basic feasibility of the notion of a hierarchical symbolic simulation. Second are the representational issues involved in describing the model. Finally, the interaction between the simulator and the rest of the MACH-III tutoring system must be specified. These three areas are addressed in the following paragraphs.

#### 5.3.2.1 Feasibility

We plan to build a hierarchical simulator that gives the virtual appearance of three concurrent simulations. The three simulations are proceeding at the *subsystem*, *functional*, and *replaceable module* levels respectively. During the course of a given simulation, every part of the HAWK will be simulated at one particular level. Parts at higher or lower levels will be capable of inferring their state, on demand, based on the state of the part actually being simulated and meta-knowledge of the simulator.

At any level we will be modeling a group of "black boxes", called *components*. Components will communicate with one another via an *interface*. During the course of this exposition, if it does not matter whether we are discussing an *interface* or a *component* we simply refer it to it as a *part*.

In our scheme of hierarchical representation, a particular *subsystem* will be composed of its components at the *functional* level. The *interface* between *subsystems* will be composed of the *interfaces* between their respective *functional components*. Similarly, a *functional component* will be composed of the components at its *replaceable module* level. The *interface* between *functional components* is made up of the *interfaces* between their *replaceable modules* (i.e. the interconnecting cables, which are themselves a special kind of *replaceable module*).

The first major problem arises from the fact that the hierarchical breakdown implied by these definitions does not exist in the strict sense. This is seen when moving from the *functional* level to the *replaceable module* level. In several areas of the HIPIR (e.g., the signal processor) some of the *replaceable modules* play a role in several of the *functional components*. In other cases (e.g., the receiver front end) *replaceable modules* are found to exist within other, larger *replaceable modules*. It will be important to avoid implementations of the simulator which rely on a strict hierarchy of levels, since the *functional* and *replaceable module* levels are really different ways of looking at the radar circuits which are occasionally hierarchically related.

A second major problem is related to vocabulary. The objects of the simulation are very different things at each level. For example, it is not easy to imagine how to express relationships across different levels, such as how a a faulty *main nulling driver* at the *replaceable module* level might cause a faulty *receiver* at the *subsystem* level. However, if the thesis that the expert does indeed maintain models of the HIPIR at differing levels is correct, then this problem must be addressed and resolved. Fortunately, the fact that the HIPIR is organized so that these relationships actually exist encourages us to believe that we will succeed in finding general ways of describing them at a level of specificity appropriate to the troubleshooting task.

The third major problem is computational economy. Simply stated, it may be cheaper to actually simulate a *part* in terms of its component *parts* and summarize, rather than to labor to describe abstractions of aggregate behavior which fit the multilevel simulation model. We believe it is important to adhere to the multilevel model to facilitate the generation of explanations with cognitively appropriate degrees of specificity. We expect that this can be done with reasonable utilization of computational resources.

Let us briefly describe how such a simulation would be designed. For each *part* in the simulation, regardless of the level, we assign two state parameters: *repair* and *validity*. The *repair* parameter denotes the existence of a fault in the *part*, it takes on two values: WORKING or BROKEN. When BROKEN there are attached values that tell why it is broken, how it is broken, and how the broken state effects the performance of the *part*. The *validity* parameter indicates if the part is doing the right thing. It also takes on two values: VALID or INVALID (it may be necessary to introduce a third value: SOMETIMES). Similarly when a *part* is INVALID there is attached data describing the *invalidity*. A *part* may be WORKING but INVALID; such a case arises when a related *part* is BROKEN.

The attached values to the anomalous values for each parameter has a data dependence flavor to it. In particular tracing the reasons for an *invalidity* should ultimately lead to a BROKEN part. It is conceivable that one part *breaking* may cause another part to become BROKEN; in such cases the dependency information would reflect that causal connection.

The values of these state parameters comprises much of the meta-knowledge that would be used to give the illusion of three concurrent simulations. Each *part* in the simulations would be able to summarize the its own *state* parameters in terms of the component *parts*. The component *parts* of a completely WORKING and VALID *part* are all WORKING and VALID and their behavior may be inferred on demand by any means that is convenient.

A BROKEN part, by convention, will know how to behave.

An INVALID part, also by convention, will know how it is to behave by interrogating the the reason for its invalidity.

Simulation of the HIPIR system and subsystem BITE could be extremely difficult and complex. Fortunately, it is possible to adopt an indirect strategy and simulate the actual simulation of BITE operation. In this way the simulation of the BITE test can be accomplished by interrogating the *repair* and *validity* parameters of the appropriate *parts* and applying an inferential model of the BITE to derive the correct BITE indications. These considerations indicate that a probe specified by the fault isolation procedures (FIPs) from the relevant TMs could be similarly simulated.

### 5.3.2.2 Representation

The second major research issue in the development of the simulator deals with representation of the model. It is desirable to establish some modularity in the MACH-III. This modularity will make it easy to modify the tutor as changes occur in the design of the HIPIR and will support the development of tutors for other large and complex electronic systems. A decomposition of the simulator is required in the same way we decompose an expert system into an *inference engine* and a *knowledge base*.

Applying this notion in terms of the simulator will lead to the development of a simulation processor and a distinct simulation language. Rather than build an embedded language within Lisp, we will extend the graphics editor of STEAMER to provide an intelligent front end to the model builder. The editor will present a stylized representation of the part to be modeled, while maintaining data structures and Lisp code in the background.

A knowledge base of abstractions for electronic parts will be built with the language processor. This knowledge base will be useful for quickly building the real parts of the model. It will be developed using a representation system like that of KL-ONE.

#### 5.3.2.3 Interaction with MACH-III

The HIPIR simulation is only one component of the MACH-III tutor. During a lesson the tutor must also maintain a student mental model, maintain an expert mental model, discriminate differences in the mental models, set tutorial goals, and interact with the student. The state of parts being simulated contributes to these tasks.

The representational language will provide forms that relate the part being modeled to these other functions. These forms will be used in building a complete representation of the part. For example, the state information of the part could be used by the expert to present some fact to the student and by the tutor to understand why a student is attempting to take some action. The ability to instantiate parts as either BROKEN or INVALID and to relate them to the expert model is essential to lesson preparation.

The representation of trouble shooting knowledge relates to the representation of the simulation model. Current thought suggests attaching to the actual part being modeled the procedure for trouble shooting it. We plan to generalize the trouble shooting knowledge within the abstraction lattice. These generalizations can be used to elucidate the process of trouble shooting in terms of broader principles.

## 5.4 Subject Matter

The subject matter of HIPIR operation and maintenance must be analyzed to extract the system-specific information required to support operation of the articulate expert troubleshooter and the symbolic simulation. The following subsections address activities required to support this phase of MACH-III development.

### 5.4.1 HIPIR Structure

The primary reference for information about the structure of the HIPIR is the series of Government published TMs. Four of these are relevant to some aspect of subject matter development:

- TM 9-1430-1533-12-1 presents the overall layout of the components of the HIPIR, including control panels. This TM provides detailed directions for operation and routine checkout and adjustment of the radar.

- TM 9-1430-1533-12-2-1 (C) explains the theory of operation of the HIPIR at the level which is taught to the 24C, and presents functional schematic diagrams of the radar at three different levels of detail.

o TM 9-1430-1533-12-2-2 contains the detailed FIPs for the HIPIR.

o TM 9-1430-1533-12-3 contains the actual wiring diagrams for the HIPIR>

Of these documents, the first three actually appear to be most useful to our work. The fourth is an important supplementary reference to assist in building accurate representations of complex signal paths. Fortunately, very little of the contents of TM 9-1430-1533-12-2-1 is actually classified. Unfortunately, significant parts of this TM are grossly inadequate from both the technical and cognitive viewpoint. We believe, but cannot confirm, that the most severe of these inadequacies arise from an attempt to provide a complete discussion of the radar without actually disclosing the mission-related purpose of significant parts of it. These undisclosed purposes appear to relate to the ECCM features of the radar.

Since the simulation of the HIPIR will operate at the *subsystem*, *functional*, and *replaceable module* levels, an accurate body of such information about the radar must be developed. TM 9-1430-1533-12-2-1 provides an overall block diagram of the HIPIR (Figure 12-1) which, with the assistance of USAADASCH subject matter experts, appears to be developable into a reasonable basis for the *subsystem* level simulation. Figure 3-1 shows a typical *subsystem* level model abstracted from this source. While we have established that this diagram is not entirely adequate, it is illustrate of the level of detail we envision at the *subsystem* level.

TM 9-1430-1533-12-2-1 also provides a series of diagrams which can, with supplementary basis, form the basis for analysis of the HIPIR at the *functional* level (Figs. 12-2, 12-15, 12-21, 12-26, 12-30, and 12-37.). Figure 3-2 shows a typical *functional* level model abstracted from this source for the RCVR. Again, this diagram is not entirely adequate to accomplish the desired representation, but indicates the approximate level of detail we find relevant.

The fine tuning of *functional* level models and the development of *replaceable module* level models requires the careful analysis of a series of diagrams from TM 9-1430-1533-12-2-1 which show the actual functional schematics of various HIPIR subsystems. These diagrams must be compared to the FIPs of TM 9-1430-1533-12-2-2 to identify the field-replaceable modules on which the 24C is authorized to operate in the conduct of organizational maintenance, to enumerate the interconnecting cables and connectors which play a role in 24C activities, and to rationalize system boundaries between *functional* and *replaceable* entities. The results of such an analysis for the RCVR are depicted in Figure 3-3.

At the *subsystem* level each system component is additionally characterized by its control panel, and the switches, lamps, knobs, meters, and dials there represented. A few *parts* at other levels may also have attached indicators and controls. The primary source for this information is TM 9-1430-1533-12-1, which contains pictures and explanations of all such interfaces of the HIPIR.

The most important additional information required to specify HIPIR structure and operation for the purposes of simulation is data describing the various fault modes of the various defined *parts*, the effects which they have on signals within the radar, and the effects which various classes of faulty signals have on the operation of other *parts*.

The primary source for this information, at least initially, will be the symptom lists presented in the FIPs of TM 9-1430-1533-12-2-2 and the operational instructions of TM

9-1430-1533-12-1. We will supplement this information, as needed, with our own analyses of HIPIR operation and with information gleaned from Government subject matter experts.

## 5.4.2 Practical Troubleshooting Doctrine

The various TM's associated with the AN/MPQ-57 RAM/HIPIR present a complete system for troubleshooting the radar. Unfortunately, this troubleshooting system displays a number of major shortcomings:

- it fails to allow for the incorporation of knowledge specific to particular radars and radar sites,
- it requires a high level of verbal ability for effective utilization,
- it is designed with seemingly little regard for the cognitive problems of understanding and utilizing its content
- it provides no guidance about effective action once the prescribed remedies have been exhausted,
- it is packaged in a manner which is inherently difficult to use in inclement settings, and
- all information about diagnostic strategy and overall troubleshooting goals has been systematically purged from its checkout and maintenance procedures.

Since it is clearly impossible or impractical to rely solely on the standard series of TM's as a guide to organizational maintenance of the radar, and since it is also impossible or impractical to undertake radar repair without access to these reference documents, we sought to discover an efficient, practical method by which the TM's and other knowledge sources are incorporated into the troubleshooting process.

We approached this problem initially by interviewing 24C's with varying degrees of experience at USAADASCH. While our results in this area are preliminary and require verification and refinement, they are indicative of factors and viewpoints which will guide the development of the troubleshooting expert system from the subject matter viewpoint.

We were surprised to observe that no single individual verbalized a comprehensive approach to HIPIR troubleshooting. In addition, the viewpoints of each informant about the role of the various TM's varied widely. When we specifically probed the domain of each individual's greatest expertise on the job, however, a consistent pattern seemed to emerge.

We specifically asked each of five informants what actions they would take in attempting to resolve particularly difficult problems which had defied analysis and correction by the routine procedures with which they were familiar. The resulting discussions triggered by this line of questioning led us to realize that each informant was presenting a view of a common procedure, limited and colored by his own personal experience and expertise. When the various approaches were arranged for consideration in order of increasing on-the-job experience of the informants, their interrelationships became apparent.

We abstracted an overall approach to troubleshooting the HIPIR from these discussions. We call this approach a *practical troubleshooting doctrine*. A summary of this practical doctrine is presented in Appendix A. We expect to refine this description through discussion with additional 24C informants.

We believe this practical doctrine makes sense in terms of the structure of the HIPIR, the capabilities of the BITE, the overall plan of organizational maintenance, and the cognitive capabilities of the current 24C trainees. In addition, we believe it will be relatively easy to motivate and to justify the various actions of the practical doctrine in mnemonically and cognitively helpful ways. The elaborated and refined practical doctrine will play an important role in helping to structure the more detailed troubleshooting expertise to be developed by the MACH-III.

Review of the practical doctrine indicates that it effectively addresses most of the shortcomings of the basic TM's stated at the beginning of this section:

- it recognizes the role played by knowledge specific to particular radars and radar sites,
- it draws on highly verbal materials (e.g. the FIPs of TM 9-1430-1533-12-2-2) only when absolutely required to document specific complex actions,
- it organizes actions into intuitively appealing groupings which are relatively easy to understand and motivate, and are relatively efficient in their use of intellectual and physical effort,
- it provides guidance about effective action in essentially all circumstances which will be encountered in organizational maintenance of the HIPIR,
- once mastered, it can be performed without reference to large and complex documents, except when access to a specific, detailed diagnostic procedure is required, and
- it provides goals which direct troubleshooting behavior which, while not always ideal or correct from a technical viewpoint, have significant mnemonic value.

# 6. IMPLEMENTATION PLAN

This chapter provides a preliminary overview of the preparations which we will undertake during Phase 1 for the Phase 2 implementation, delivery, and fine-tuning of the MACH-III demonstrator at USAADASCH. This discussion, which is necessarily incomplete at this time, focuses on plans for formative and summative evaluation of the MACH-III demonstrator.

## 6.1 Formative Research

### 6.1.1 Definition and Goals of Formative Research

Formative research can be characterized as the investigation of those factors which contribute to or are responsible for a person's understanding and use of a product that is being formed. Hence the name, *formative* research.

Formative research methods were primarily developed and refined during the planning and production of educational television programs such as "Sesame Street" and "Electric Company". It is its intended function "...to provide information which the producers would find useful in making program-design decisions relating to both appeal and educational effect." (Palmer, 1974). Formative research methods have since been extended to other media, such as software programs.

The similarities between the two media, television and computers, are numerous; their presentation is primarily a visually dynamic one. Their auditory presentation is utilized for emphasis and feedback. The major difference is that the television medium is passive; the learner cannot influence the presentation. With the computer medium, the learner can potentially interact with and therefore, influence what is presented, given that the program is designed for this interaction. The current role of formative research in intelligent tutoring system software development is to investigate what factors are pertinent to this form of presentational learning. Additionally, the support documentation accompanying the software program will be evaluated.

Formative research is an integral part of the product development cycle. Unlike the summative approach, it is a continuous process, rather than a discrete event. The main thrust of formative evaluation is to provide an early "ballpark estimate" during product development of the product's effectiveness in presenting the desired instructional objectives.[10] Those software features which are found to impede or prevent learning are consequently re-designed and again scrutinized for their effect with the targeted population and environment. By using the formative approach, major representational errors are caught early and are redesigned, thus saving on recoding time later when the program is difficult to change. Specifically, aspects

[10] as determined by cognitive researchers

such as screen design, both within a visual display and between displays, interaction via input or output devices (mouse, menus, screens), and other related human factors issues are thoroughly evaluated. These interactions with the program influence a user's grasp of the material presented and can potentially distract/distort or enhance the user's understanding of the material.

Formative research is closely aligned with formal evaluative (summative) methods. Many of the traditional summative research methods are used to assess the product prototype; these are more descriptive methods, such as observation, questionnaires, and extensive open-ended and constrained interviews. In some sense, formative research can be viewed as pilot test. The major difference is that formative method emphasizes the presentational aspects much more than summative method does, since the results of formative research are used to influence the instructional presentation, rather than whether the instructional principles per se are valid or not. Therefore, formative research assesses how well the software medium visually and aurally expresses the instructional intent.

However, the two methods are not wholly inseparable. Implicit in formative assessment is an evaluation of not only how well the population attends to and extracts that instructional information, but how well the information is integrated and finally utilized. This, then, is the "gray area" where formative and summative research cross; if the formative evaluation of the program prototype identifies a particular concept as harder to grasp than other concepts similarly presented, this influences the cognitive and instructional principles driving the presentation. In this situation, formative research serves as a means to identify potential cognitive difficulties or misconceptions and thus influences the cognitive organization of the instruction. The interplay between these two types of evaluations is crucial and necessary to develop a useful and accurate instructional system.

### 6.1.2 Formative Evaluation of MACH-III

Early in the product cycle, the content of the visual displays will be tested with students and instructors. Icons will be tested for how well they represent actual physical components or the intended symbolic function such as a voltmeter. Evaluation of the functional diagrams will ascertain how well students and instructors comprehend the inputs and outputs of the functional components and how well the labels themselves correspond to the terminology used at the school. The layout of the replaceable module diagrams will be evaluated for how well the population can "map" from them to the radar and vice versa.

Additionally, the screen layout and the manipulation of the interface through menus and pointing devices (mouse, arrow keys, keyboard input) will be evaluated for ease of access and comprehensibility. *This evaluation will be conducted by first observing how the subject* interacts with the system, then systematically questioning the user about what features have been noticed, how to interact with them and their function. Features that are ignored will be investigated for lack of salience, misleading labels, and difficulty of access or comprehensibility.

A way to send messages to the developers for suggestions for improvement or questions will also be provided - these messages can be "tagged" to the relevant screen, if needed. Also, a record will be kept about the frequency of requests for help on particular items. This will indicate which items require an explanation or more extensive explanation.

As the simulation prototype matures and the various instructional methods are underway, they will be developed, tested, and refined:

*Demonstrations* Questioning the student immediately after observing the demonstration and after a short interval will help evaluate the accuracy, salience, and "staying power" of specific features and concepts.

*Coaching* Initially observing students solving problems with a human coaching will provide insight into various critical points during the problem solving process. The simulation will provide as much of this demonstrated guidance as possible; its effect on problem solving with the simulation and consequent problem solving on the radar will, in turn, be evaluated.

*Inquiry* Initial observation of the type of questions a human instructor asks the students, and the range of subsequent student actions will provide a basis on which to develop systematic questioning by the simulation and the menu of action options (articulation) from which the student can select. This will provide a means to stimulate students to differentiate correct from incorrect actions and to explain the basis of their differentiation. By monitoring the appropriateness of these selected actions, the student's evolving model can be evaluated. Consequent behaviors on the radar will also reflect transfer of the student's model.

*Reflection* The perceived value and the observed effect of the visual "playback" of the student's troubleshooting performance with the simulation will be assessed. Other issues pertain to whether they understand what the purpose of this feature, whether they can retrace their steps using the simulation's playback capability, whether they understand what they should have done using the playback of the ideal model's steps, and how often they refer back to these performance playbacks. The transference of these skills on troubleshooting on the actual radar will also be investigated if possible.

*Exploration* The simulation will keep track of how often the exploration mode was accessed, what was investigated, and how long the investigation lasted. By observing students in the exploration mode, a method will be developed to assist students to explore more systematically. The quality and quantity of information gleaned from exploration will be determined via descriptive evaluation. In particular, misconception from these explorations will be of special interest.

The problems presented in the context of the display views for each specific system and the overall functional view will be evaluated for their level of difficulty. Difficulty will be rated according to the following criteria:

o the conceptual difficulty

o the number of possible paths to follow

o how common the problem is

- o the number of transitions from one type of energy to another (e.g.. from electrical energy to mechanical energy)
- o the accessibility of the test point or component involved
- o the number of procedural steps involved, including tracing schematics or following the FIP[11]
- o and the functional knowledge required to comprehend, isolate, and solve the problem.

Additionally, student performance will be closely monitored for the *usefulness* of this information for troubleshooting, particularly for those parts which are inaccessible or for functions that are unobservable. The utility of this type of information is critical; the student must not be burdened with knowledge irrelevant to actual troubleshooting, since he is overloaded already.

Features such as those that provide students with "extra practice" on particular items, either alone or mixed in with other problems, will also be closely monitored for their effectiveness and frequency of use. These features can be selected by the simulation, the instructor and the student. Student may practice alone or in peer cooperative/competitive situations.

Another instructional sequencing issue pertains to how often to provide instructional prompts and how quickly to fade them in the simulation. A selectable feature to "turn off" these prompts may provide insight as to when this should be done automatically.

Closely related to this issue is that of our supporting documentation. These materials must be supportive, but not crutches that the student must depend to understand the functional relationships of the radar components (unless these become official military documents that are maintained). The student must have internalized the correct mental model to troubleshoot accurately.

Finally, when the authoring capability is underway, a protective "shell" must be developed and refined to meet the needs of the instructional staff. Formative evaluation must ascertain what they would like to change and how best to allow these modifications, considering their understanding of the simulation and time constraints.

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[11]Fault Isolation Procedures

## 6.2 Summative Evaluation

We plan to evaluate the effectiveness of the MACH-III Trainer by comparing a group of students who are taught with the trainer (the experimental group) with a group who are taught by the traditional method (the control group). 24Cs entering the school on a particular date will be matched on the basis of scores on entry examinations given by the Army. One member of each pair will be assigned randomly to the experimental group and the other will be assigned to the control group. Both groups will participate in the conferences and platform exercises as they are currently taught. In addition, experimental subjects will spend a fixed amount of time, during the course of study, working on the MACH-III. Control subjects will spend a comparable amount of time in a "study hall," during which they will review course materials on their own. (If time permits, two additional control groups will be added to help pinpoint the advantages of the MACH-III trainer: a control group that sees the computer print-outs of corresponding subjects in the experimental group, but does not interact with the trainer, and a control group that interacts with the trainer, but is restricted to exercises involving the labelling of parts.)

At the completion of the course, students in each group will be given a series of tests designed to evaluate performance in two areas: system understanding and troubleshooting. The MACH-III was specifically designed to improve performance in these areas.

### 6.2.1 Assessment of System Understanding

We expect that experience with the MACH-III trainer will enhance students' understanding of the function of the components of the radar by highlighting the flow of information within and between systems. Since the physical layout of the components does not correspond directly to their function (i.e., parts that are functionally related may be physically distant), the functional organization of the radar is not obvious to the novice. Studies at the University of Pittsburgh (Gitomer, 1984; Glaser *et. al.*, 1985) have shown that skilled troubleshooters think of the components in terms of functional units, while less sophisticated subjects are likely to classify components in terms of physical similarity or proximity.

Three tasks will be used to assess system understanding in the experimental and control groups: a card sorting task, an interview, and a diagram completion test. These procedures are adapted from studies conducted by the LRDC group at the University of Pittsburgh and are described in detail by Gitomer (1984). Two hypotheses about the benefits of the training on the MACH-III will be tested. The first hypothesis is that subjects in the experimental group will have a better functional representation of the system, while control subjects will rely more on a physical representation. A second hypothesis concerns knowledge about components that the student has only observed as compared to knowledge based on first hand experience with components. The Pittsburgh studies showed that differences between the performance of skilled and nonskilled technicians were greater on tasks involving less familiar components than on tasks concerned with highly salient aspects of the radar. One advantage of the trainer is that students can manipulate all parts of the system with equal ease. By giving students simulated "hands on" experience with components that they would handle infrequently, if at all, in the traditional platform exercises, the trainer may be able to compensate for limited practice on the actual radar. The second hypothesis, therefore, is that differences in knowledge shown by the experimental and control groups will be particularly pronounced for aspects of the system that students have had little opportunity to manipulate in the real system (e.g., high voltage components, occluded parts).

#### 6.2.1.1 Card Sorting Task

This task will be administered first, since it is the most open-ended. Students will be given cards, each containing the name of one component of the radar system, and will be asked to sort the deck into piles of items that "go together." They will be asked to sort the cards again in the same way until they have achieved two identical sorts in a row, to ensure a stable grouping. Students will then be asked to explain their categories. Upon completion of this task, they will be asked if any of the piles could be combined. Explanations for these higher level groupings will be sought. The components to appear on the cards will be selected, if possible, to accommodate both physical and functional groupings. It is expected that the experimental group will organize and justify their categorization on the basis of the functional relationships between the parts while the control group will rely more on physical similarity and proximity of parts as a basis for grouping. It is also possible that the control group will require more trials to reach the criterion of two identical sorts, suggesting that they do not have a stable model of the radar. A group of experts will also be asked to sort the cards, to lend support to the notion that functional groupings are more sophisticated than physical groupings.

#### 6.2.1.2 Components Interview

In individual interviews, students will be asked to discuss different components of the radar system in terms of: physical features, function of the component, how the component works, which components affect it, which components it affects, and what major system it belongs to. Included in the list of components will be parts that students have actually worked with and parts they have been told about but have not actually manipulated. The percentage of answers that are correct will be calculated for each category (e.g., physical, functional, operational) for frequent and infrequent components. It is expected that the performance of experimental subjects will exceed that of the control subjects, particularly on the infrequently encountered components, and especially for the functional questions.

#### 6.2.1.3 Diagram Questions

This task will be given last because it is the most specific. Subjects will be given functional diagrams of each of the major components of the radar system, with all boxes labelled correctly, but with the connections between boxes missing. Subjects will be asked to draw in the connections, using arrows to indicate the direction of influence. They will be asked to explain the connections. If the subject has not described all the connections in terms of the correct flow of information, he will be given the same task again, but this time labels for the connections will be provided. The subject's task will be to indicate where each of the labels belongs.

It is expected that experimental subjects will produce diagrams showing the correct flow of information between parts, since they have had ample opportunity to experiment with the system on the Trainer. Furthermore, it is expected that they will perform well, whether or not labels are provided.

Control subjects, on the other hand, may not spontaneously think of the system in terms of information flow, because this kind of information is not obvious, when working with the actual radar. Studies at the University of Pittsburgh (Gitomer, 1984) and our own observations at USAADASCH, suggest that novices tend to think of the system in terms of power connections rather than in terms of the flow of information. Their diagrams, therefore, may include connections to the power source that are generally omitted by the experts.

It is expected that subjects in the control group will be able to describe the flow of information to some extent, when prompted by the labels, though performance will still fall short of that of the experimental group.

### 6.2.2 Assessment of Troubleshooting Skills

Troubleshooting proficiency will be observed in two ways. First, subjects will be given a set of hypothetical problems to solve. In each problem, a symptom of malfunction in the radar will be described and the subject's task will be to figure out the underlying fault. The subject can ask the examiner for the outcome of any test or procedure that seems relevant, until the problem has been diagnosed correctly. The procedure, in other words, resembles a game of "twenty questions." The advantage of this procedure is that subjects can be given repair problems that would be be too time consuming in practice. Another advantage is that the moves are easily recorded. It is expected that experimental subjects will be more efficient and more accurate than control subjects in solving the hypothetical problems because they will have the framework for generating diagnostic questions and making sense of the answers.

Secondly, problem solving will be observed on the actual radar. Since students are tested at the completion of the course on their ability to find and correct faults planted by the instructor, we can compare instructor ratings for control and experimental groups on various skills measured by this test. It is expected that experimental subjects will score higher than control subjects and will show evidence of more systematic and thoughtful troubleshooting strategies.

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# Appendix A

# A Practical

# Troubleshooting Doctrine

1. Most individual radars, operated in specific environments (e.g., Ft. Bliss, West Germany) develop consistent and commonly recurring faults which can be anticipated when the maintenance call first comes from the TAC site. To the extent the problem is immediately identified as falling in this category (e.g., water in the transmitter waveguides), the appropriate corrective measures will be taken without detailed analysis.

Frequent faults will occur in the waveguides (chronic arcing), the high voltage power supplies, high voltage connectors, and the low voltage power distribution circuits (especially 28 volts, which is routed throughout the HIPIR). These faults should be understood and corrected before attempting any of the BITE and FIP procedures outlined below.

2. In general, the person calling for 24C assistance will not have a symptomatic description of radar malfunction which is sufficiently detailed to support fault diagnosis, so the first step is to begin the daily checks. Usually, this will disclose a malfunction through the operation of the BITE, the low voltage test circuits, the fuses, etc. If it does not, continue with the weekly checks. Let us assume the routine checks yield some indication.

3. For each indicated fault, perform the first indicated procedure, either an alignment adjustment or a module replacement (except for power faults, which have their own checkout logic). Usually, this corrects the problem. Return to and continue with the routine checks.

3.1. If the identical fault recurs, and a module was replaced, put the original module back in the HIPIR before proceeding. Continue the trial replacement procedure using data in FIPs, as modified by experience. Normally, next make a trial replacement of the subsystem BITE card, followed by appropriate other cards. If all this fails, proceed to trial exchange of related modules and to test of relevant connectors and cables, using either the procedures in the FIPs, or following the wiring diagrams, or (is some cases) being guided by experience to establish the sequence of checks.

3.2. If an identical fault recurs, and an adjustment was made, consult the FIPs for a menu of appropriate checks, or derive ideas from the schematics, or proceed with tests derived from experience, if relevant.

4. If no amount of individual module replacement (with appropriate adjustments and cable testing) enables the HIPIR to check out properly, the 24C may choose to make conditional replacements of single, larger functional assemblies until a test good condition is achieved. The procedure is to replace one or several modules at a time. If a given replacement fails to correct the problem, the changed modules are left in place while additional replacements are made. The source of replacements can be spares or parts from a known-good radar; however, parts from another radar are only used with the approval of the

responsible CWO. It is important to keep a record of all replacement actions in the order in which they are performed.

4.1. Alternatively, the 24C may try returning to the basic checkout procedure and carefully establishing the closest possible tolerances for each testable subsystem and signal, replacing (unconditionally) any component which cannot be brought within specification.

5. If the identical fault does not recur, proceed with the routine checks, treating additional faults in the same manner. At the conclusion of this process, all faults detectable by the BITE and related systems will have been isolated and corrected, and the HIPIR will usually operate correctly.

6. If the HIPIR tests good, but will not perform a combat-critical function correctly (if the impaired function is not combat-critical the HIPIR is normally returned to service at this point), the symptoms of the malfunction must be characterized by careful observation, usually performed by a team (one person in the BCC and one or more at the HIPIR, communicating by phone).

7. Once the malfunction is understood, identify the possible contributing subsystems and perform standard tests and adjustments to bring each component within spec at all measurable points. Any component which cannot be adjusted to spec is replaced. If the malfunction persists, in-spec components are replaced until the symptoms are eliminated.

8. The HIPIR is tested after every replacement action. The last component replaced is one of the faulty ones. With a full understanding of the risks involved, one can then swap back in all the other replaced modules one at a time, beginning with the in-spec ones and working backwards until a fault reoccurs, at which point the last module swapped back is presumably also defective. Since some multiple faults induce other faults, this is a very risky operation which would not normally be performed unless combat readiness is not critical at this time, a large number of apparently good modules have been replaced, and a knowledgeable (and confident) senior warrant officer is supervising the activity.

9. The TIC BITE function is performed by use of the approach/recede switch as described in the FIPs. TIC faults are uncommon and relatively easy to identify and correct by module replacement according the the FIP or experience-derived principles. The TIC will become digital in the PIP 3 HIPIR.